Laser plasma sources of soft X-rays and extreme ultraviolet (EUV) for application in technology and science

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Laser-Matter Interaction Group (LMI)

Research topic – Generation of X-rays and extreme ultraviolet (EUV) with lasers

Goal – Development of laser plasma sources of X-rays and EUV for application in science and technology

Group members

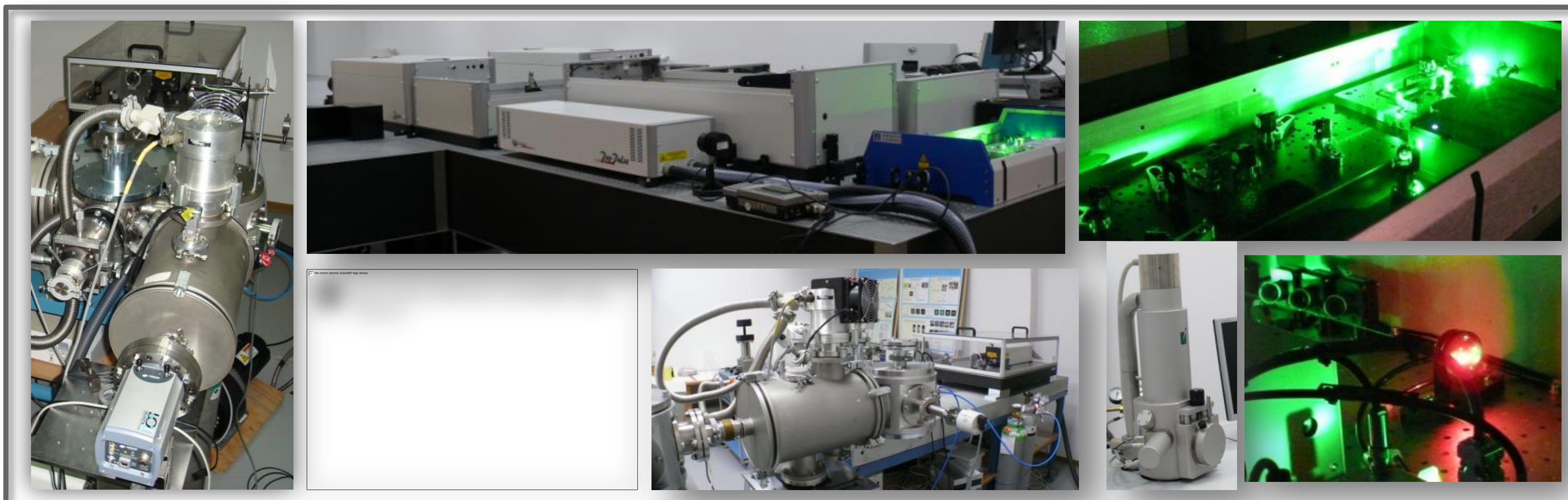
Prof. - Henryk Fiedorowicz

Dr. - Andrzej Bartnik, Roman Jarocki, Jerzy Kostecki, Mirosław Szczurek, Przemysław Wachulak

M.S. **-** Daniel Adjei (PhD), *Inam Ul Ahad (PhD)*, Mesfin Getachew Ayele (PhD), Tomasz Fok (PhD), Anna Szczurek, Ismail Saber (PhD), Alfio Torrisi (PhD), Łukasz Węgrzyński (PhD)

Adm. - Karolina Płatek

http://www.ztl.wat.edu.pl/zoplzm

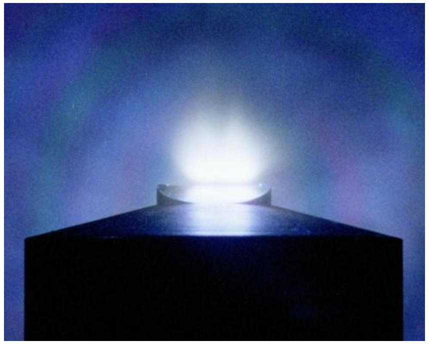


OUTLINE

- **Introduction**
  - soft X-rays and EUV
  - laser plasma soft X-ray/EUV source
  - gas puff target

- **Metrology**
  - characterization of EUV mirrors
  - EUV mirror degradation
- **Imaging**
  - EUV microscopy,
  - soft X-ray microscopy,
  - soft X-ray contact microscopy,
  - EUV radiography and tomography,
- **Processing materials**
  - microfabrication,
  - modification of polymers for biomedical control,
  - modification of magnetic materials,
- **Photoionization studies**
  - EUV induced luminescence,
  - EUV induced photoionized plasmas,
- **Radiobiology**
  - DNA damage with soft X-rays

- **Conclusion**



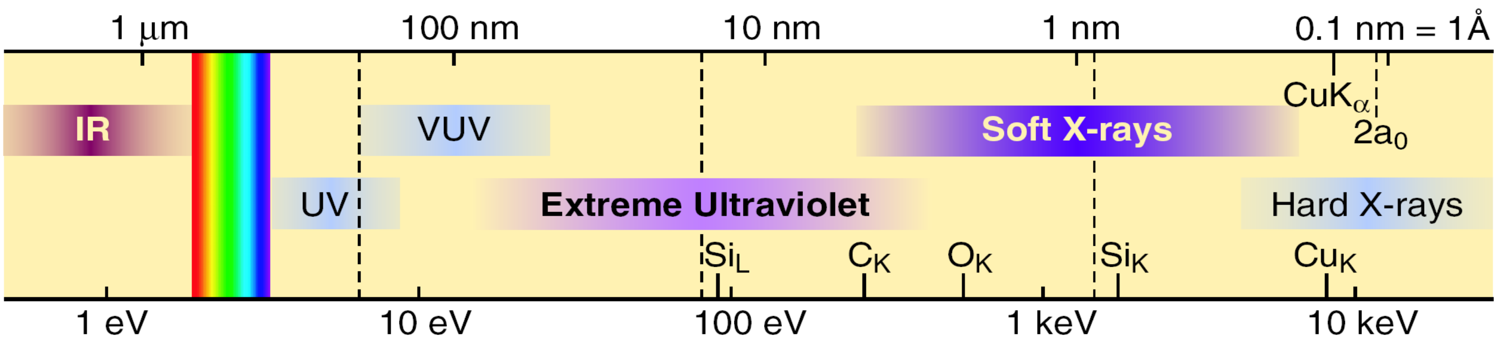
Introduction

• soft X-ray and extreme ultraviolet (EUV) wavelength ranges

ISO International Standard 21348 http://www.spacewx.com/ISO_solar_standard.html

Soft X-rays (XUV)	$0.1 \leq \lambda < 10$ nm
Extreme Ultraviolet (EUV)	$10 \leq \lambda < 121$ nm (He Lyman-alpha)

D. T. Attwood *Soft X-rays and Extreme Ultraviolet Radiation: Principles and Applications* (Cambridge University Press, Cambridge, 1999)



Nanowaves

• motivations

- nanometer resolution (nanolithography & nanoimaging)
- nanometer penetration depth (processing of surfaces & nanoanalysis)
- elemental mapping (nanoscale)

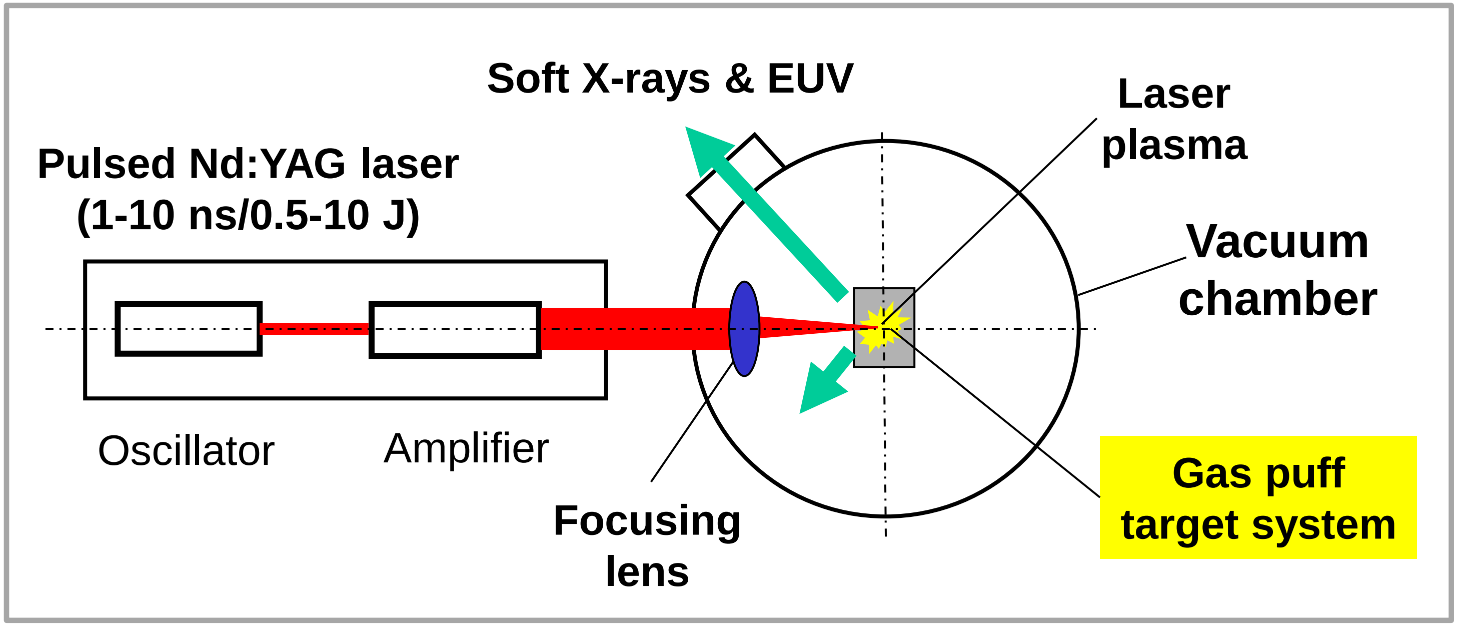
EUV lithography

• generation

- synchrotrons, FELs
- plasma sources (discharge plasmas, **laser plasmas**)

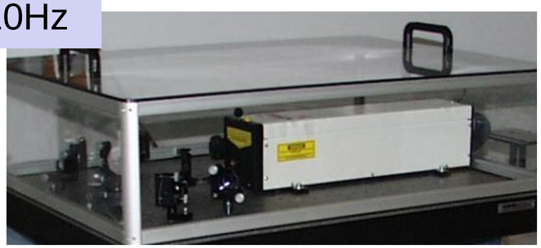
Laser plasma soft X-ray and EUV source

• schematic of the source



We use commercial Nd:YAG lasers (EKSPLA)

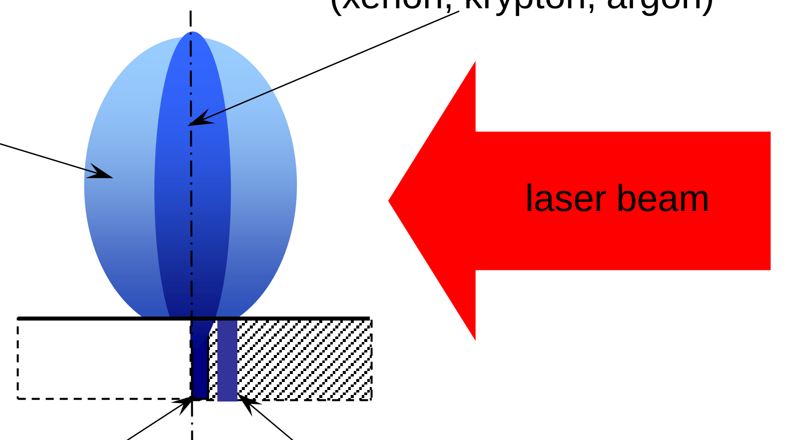
4ns/0.5-0.8J/10Hz



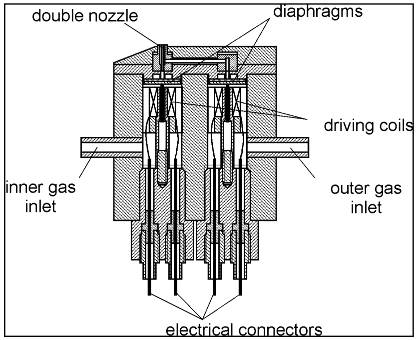
2-10ns/10J/10Hz

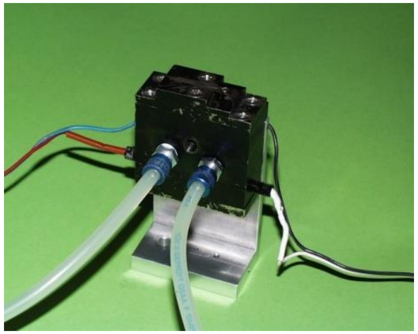
Double-stream gas puff target

- **schematic of a double-stream gas puff target**

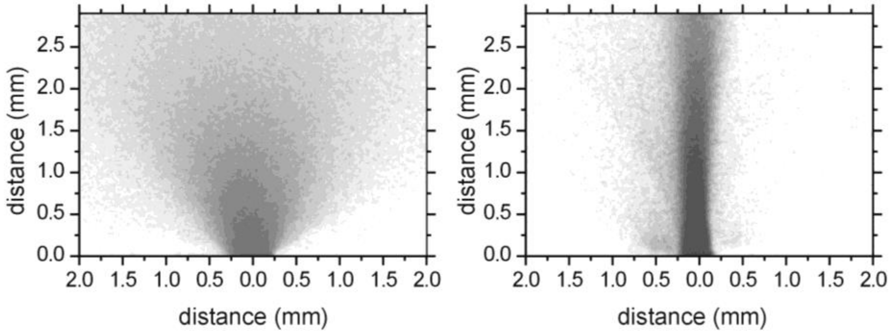


- **electromagnetic valve system**





- **X-ray backlighting images**

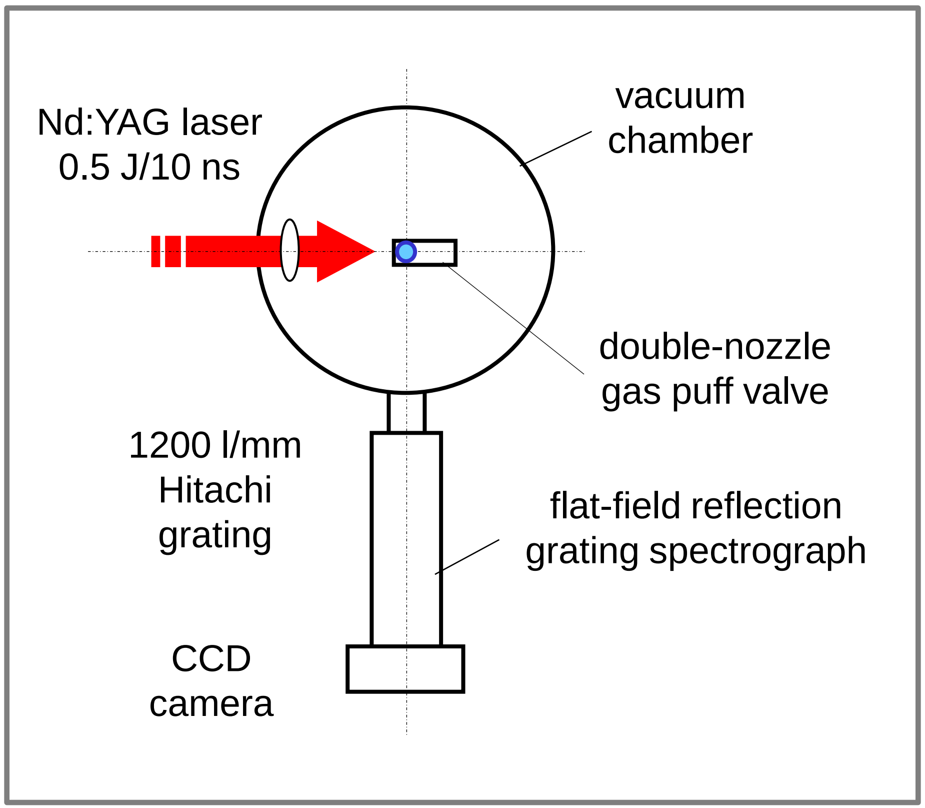


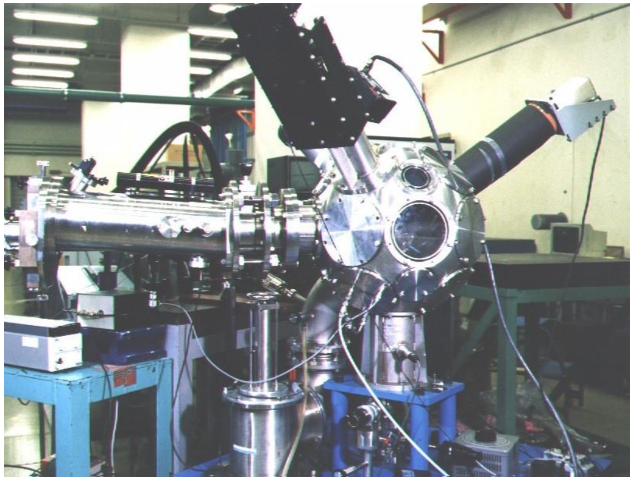
H.F. et al., *Appl. Phys. B* ***70*** *(2000) 305; Patent No.: US 6,469,310 B1*

EUV emission studies

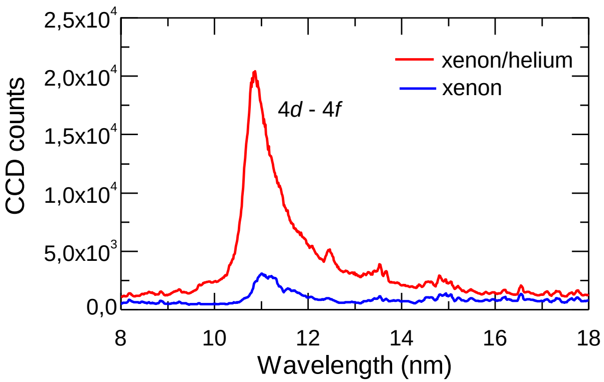
- **Institute of Laser Engineering, Osaka, Japan**

Experimental setup





EUV spectra

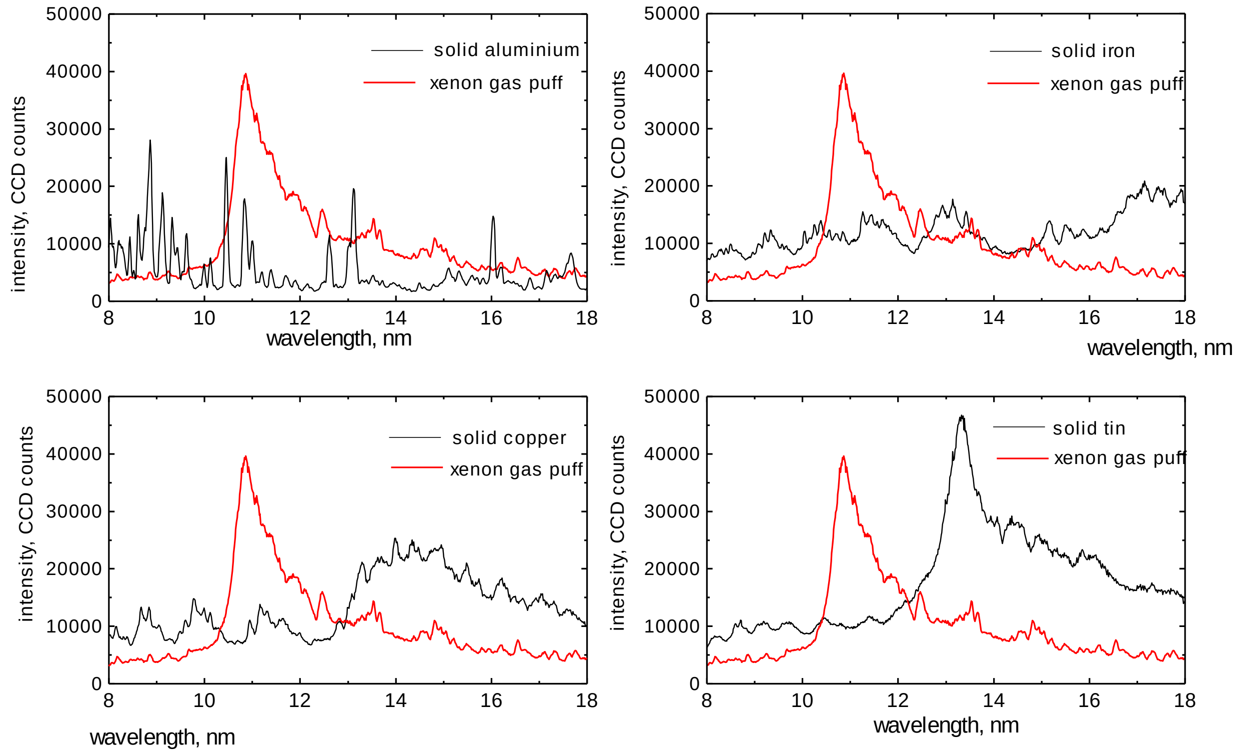


Collaboration with Hiroyuki Daido

H.F. et al., *Opt. Communications* ***164*** *(2002) 161*

EUV emission studies

EUV emission from various targets irradiated with a Nd:YAG laser (0.5J/10ns)



ILE, Osaka

IOE, Warsaw

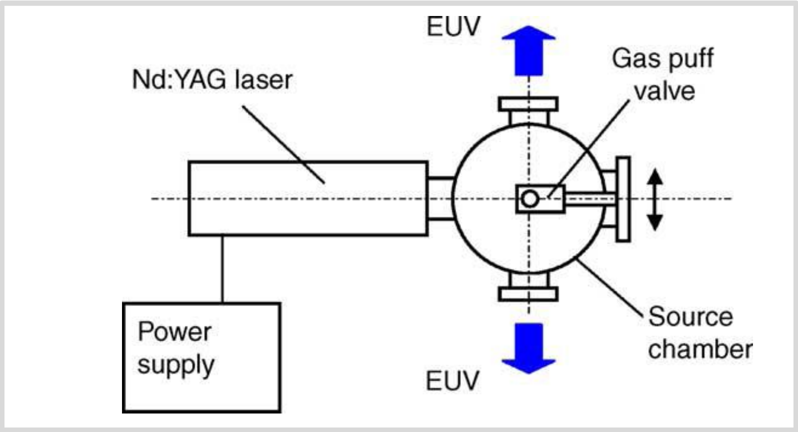
Gas puff target

- **Elimination of debris production**
- **Easy operation with repetition**
- **Conversion efficiency improvement**

H.F. et al., *Opt. Communications* ***164*** *(2002) 161*

Laser plasma EUV source

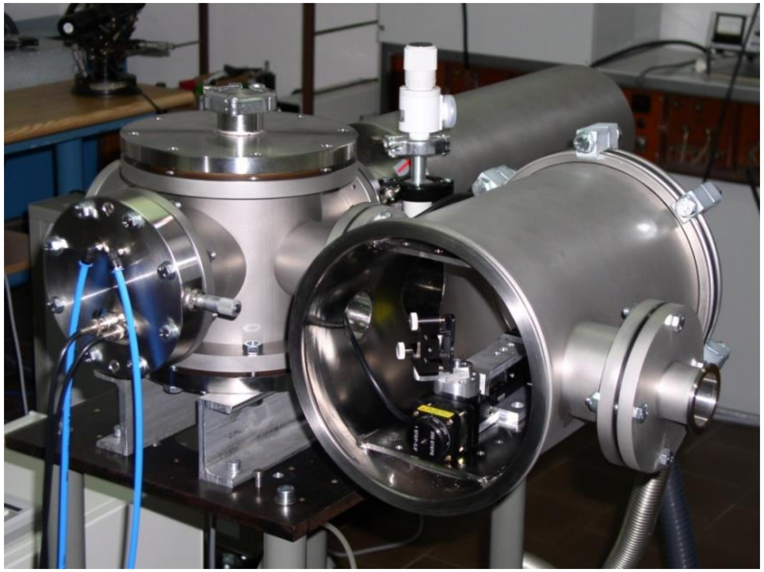
- compact laser-plasma EUV source with a gas puff target irradiated by a Nd:YAG laser (4 ns/0.5 J/10 Hz)



10cm

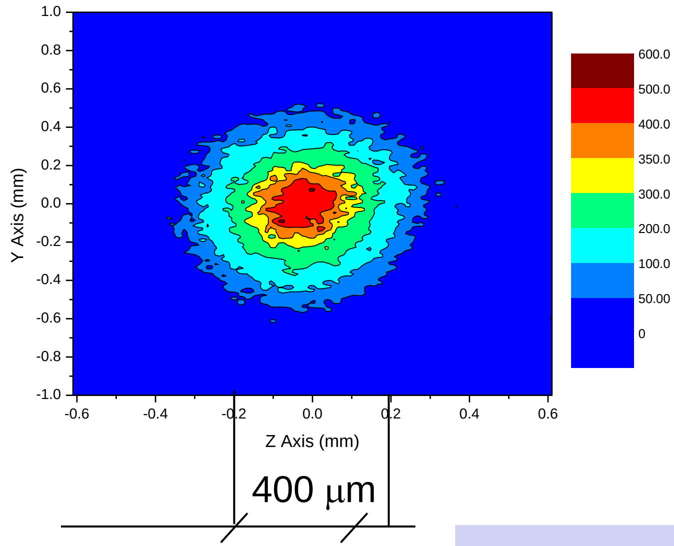
EUV lamp

EUV metrology setup

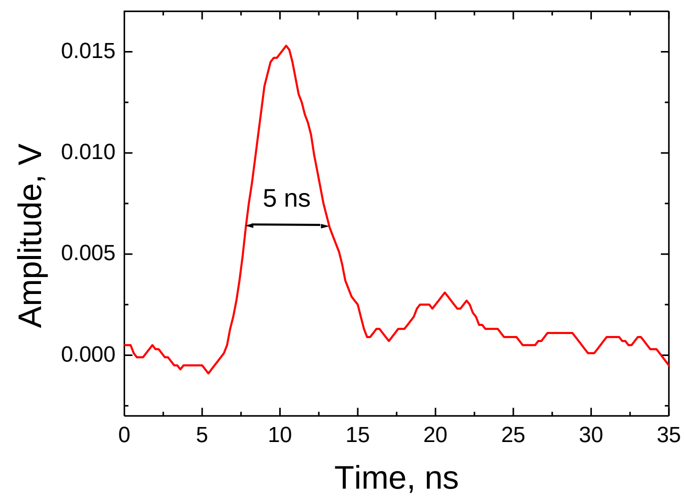


EUV source characterization

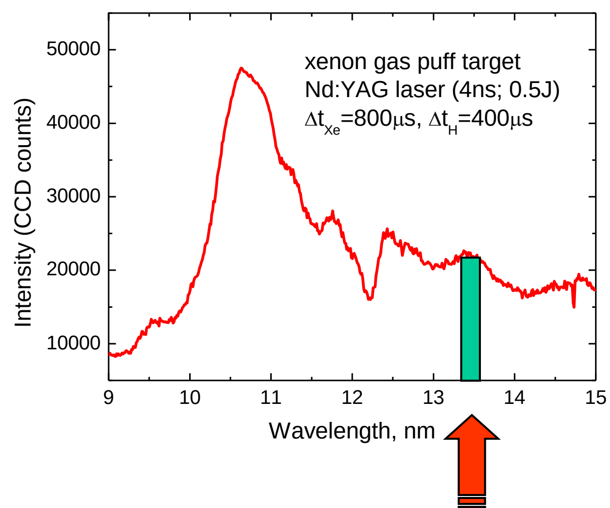
Spectral image at 13.5 nm



Time profile



EUV spectrum



CE for EUV

~ 20 %

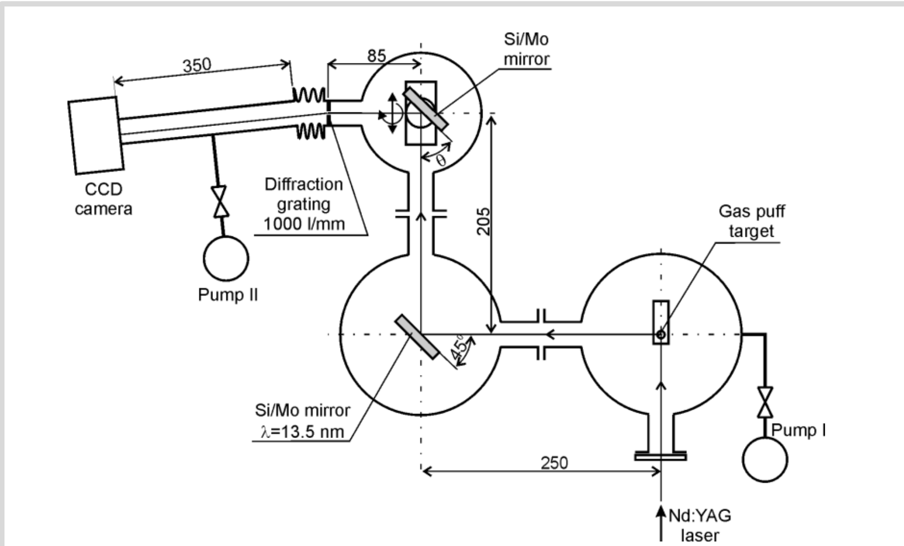
CE at 13.5 nm

~ 1.5 %

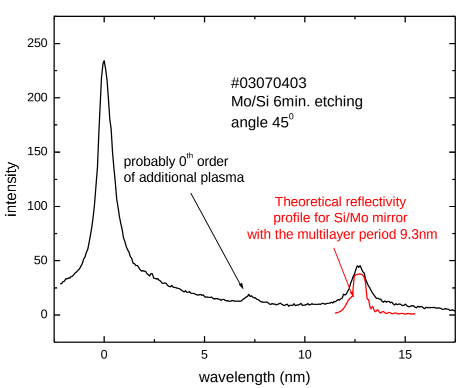
H.F. et al., *J.Alloys&Compounds* ***401*** *(2005) 99*

Application in EUV metrology

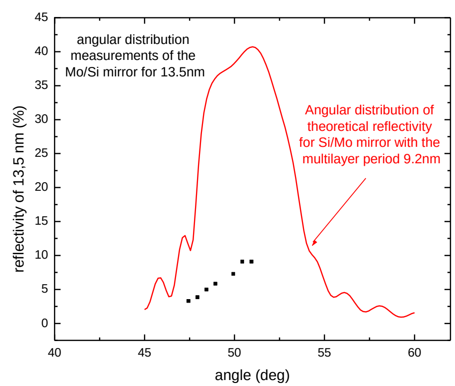
- characterization of Mo/Si multilayer mirrors



- spectral distribution at 45°

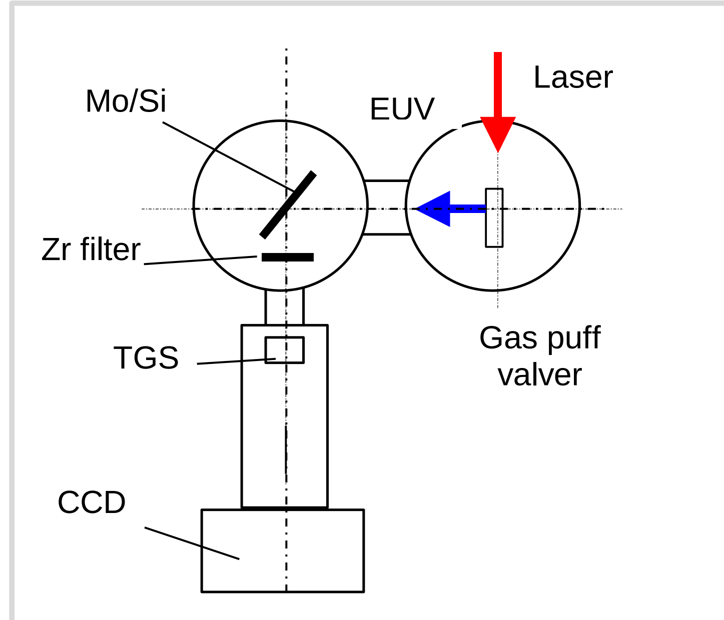


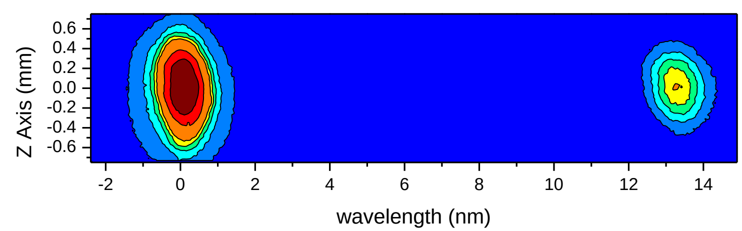
- angular distribution at 13.5nm



Collaboration with REFLEX s.r.o. Prague, Czech Republic

- degradation of Mo/Si multilayer mirrors irradiated with EUV pulses



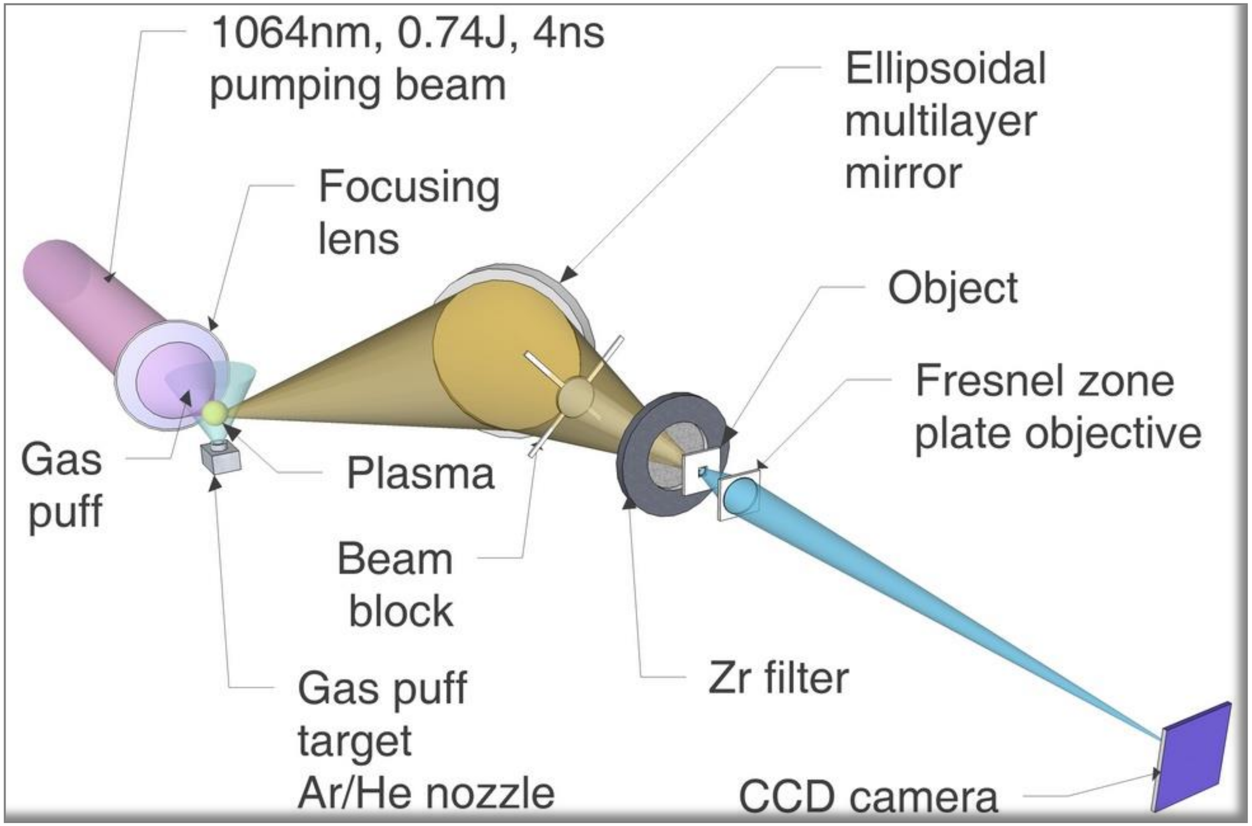


Collaboration with IOF, Jena, Germany

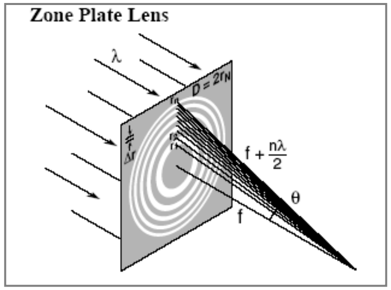
R. Rakowski *et al., Optica Applicata* ***36*** *(2006) 593*

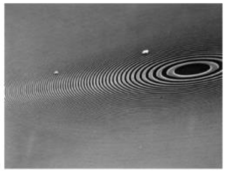
Application in EUV nanoimaging

Schematic of EUV microscope based on a Fresnel optic



Zone Plate Lens



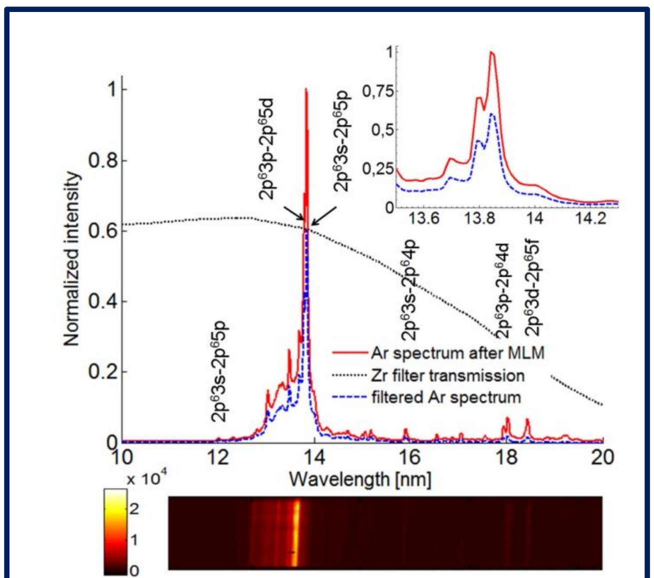


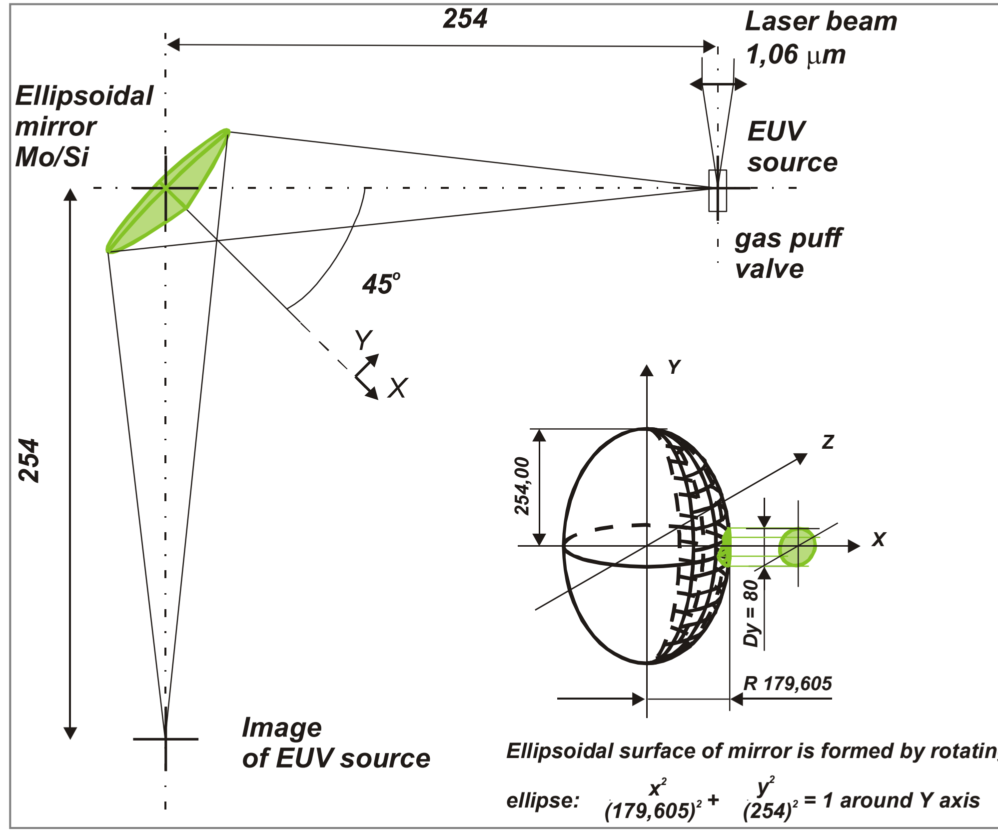
Zone plate parameters:

Diameter: 200 mm
Outer zone width: 50 nm
Focal length: 0.724 mm
Number of zones: 1000
Numerical aperture: 0.137
Theoretical resolution
(Rayleigh criterion): 61 nm
Depth of focus: +/- 385 nm

EUV optical system

Ellipsoidal mirror with Mo/Si coating





Quasi-monochromatic EUV emission

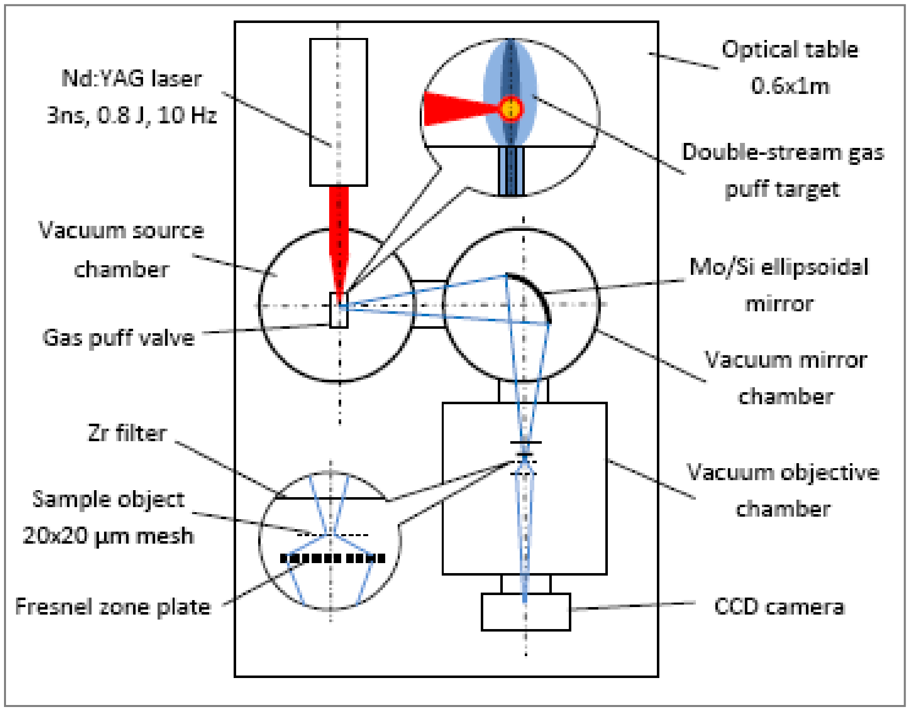
Photon flux ~8.8 x 10^{10} photons at λ=13.84nm.

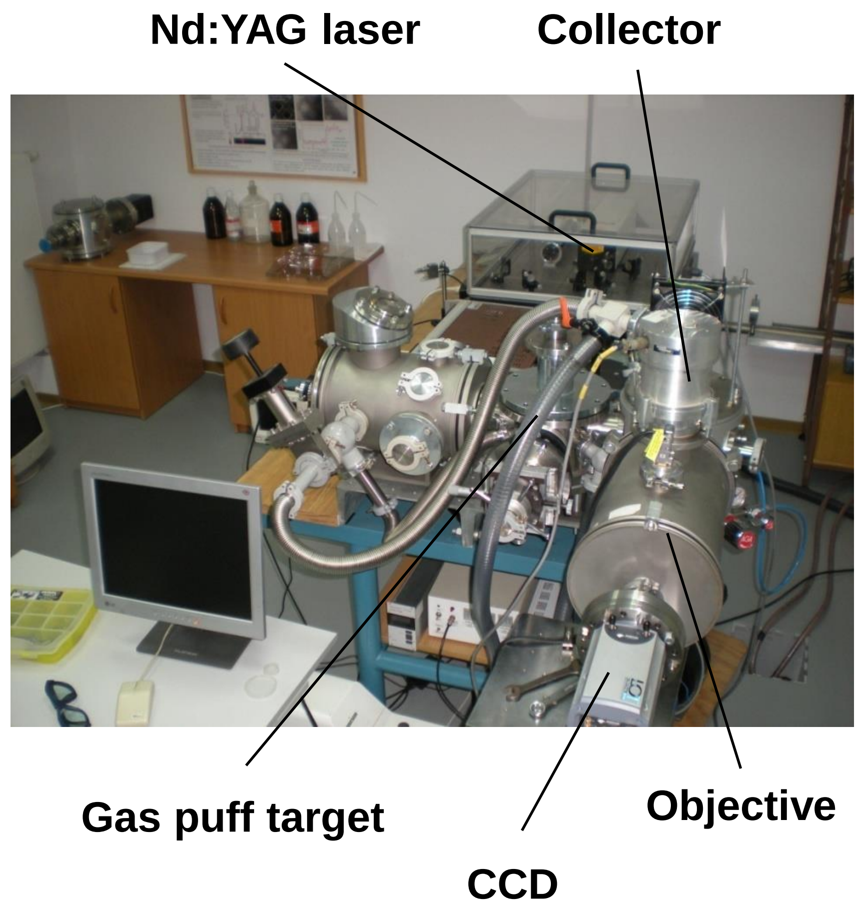
P. Wachulak *et al. Appl.Phys.B* **100** (2010) 461

Collaboration with REFLEX s.r.o. Prague, Czech Republic (substrate) and IOF, Jena, Germany (multilayers)

EUV nanoimaging

Desk-top EUV microscope with a laser plasma source





Optical table 0.6 m × 1 m

P. Wachulak *et al*. *Optics Letters* **35** (2010) 2337

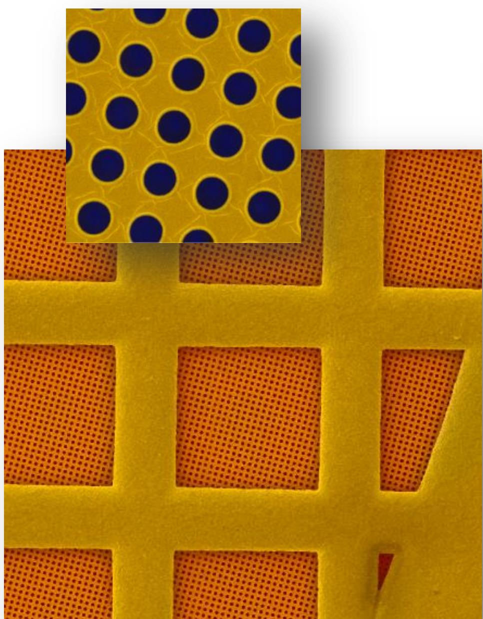
EUV nanoimaging

50nm resolution desk-top microscopy at 13.8 nm using a compact laser-plasma EUV source

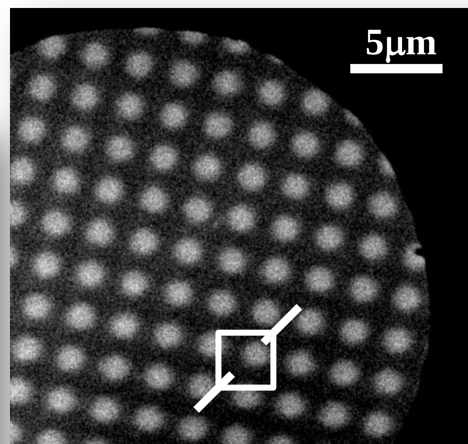
Test object

Micro-holes 1.5µm diameter, 2.5µm period structure in 10nm thick carbon film coated with 60nm of gold

SEM image



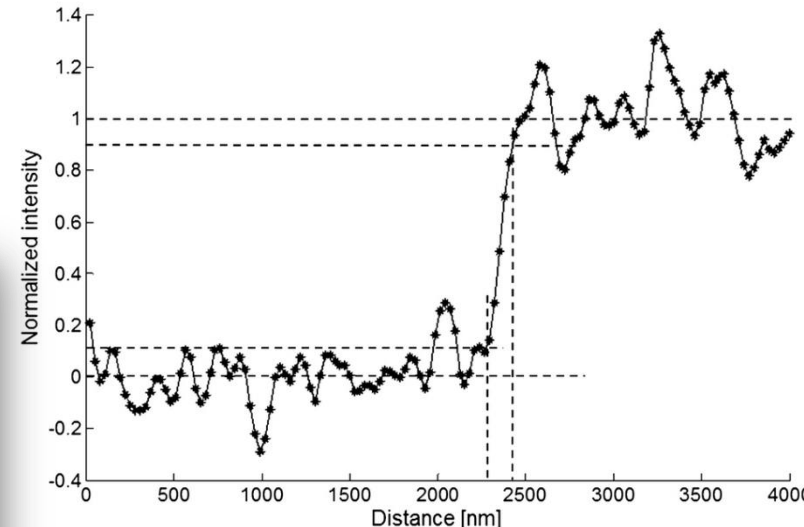
EUV image



Exposure 50sh/2Hz

Single-shot exposure possible!

Knife-edge test for EUV image



The estimated 10 to 90% intensity transition across the sharp edge is equal to 138.5nm (5 image pixels).

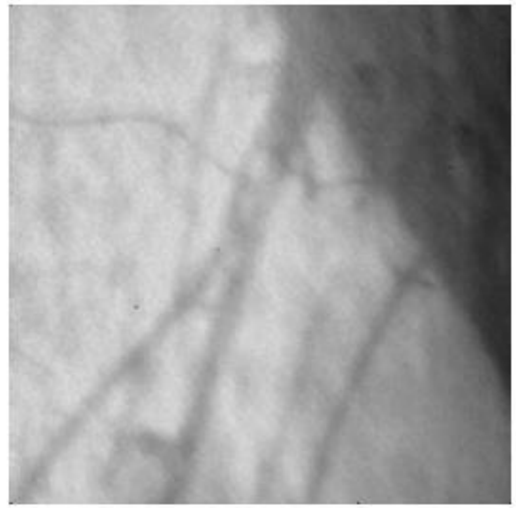
This corresponds to a half-pitch spatial resolution of the microscope equal to

51 nm.

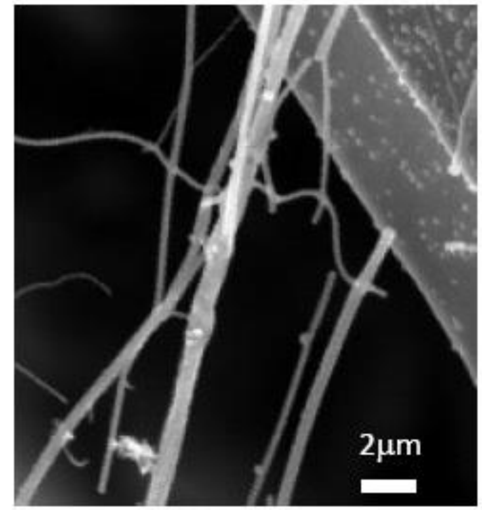
P. Wachulak *et a*l. *Optics Express* **19** (2011) 9541

Imaging of nanostructures: ZnO nanowires

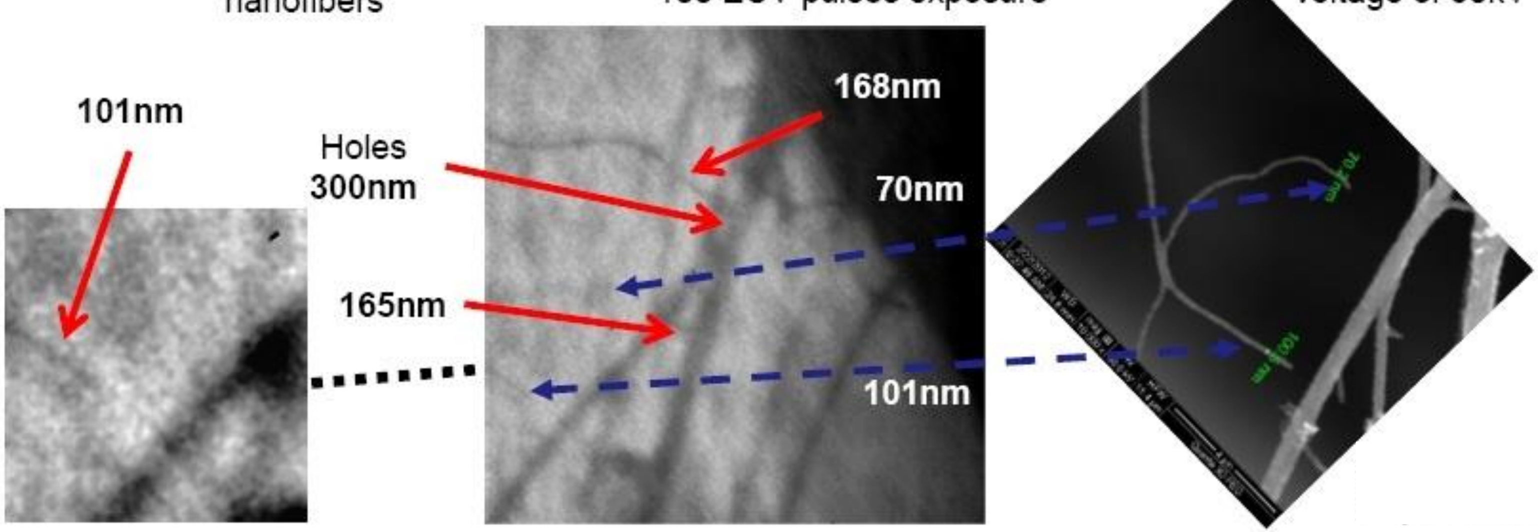
Optical micrograph of ZnO nanofibers



EUV microscope image, 100 EUV pulses exposure



SEM micrograph at accelaration voltage of 30kV

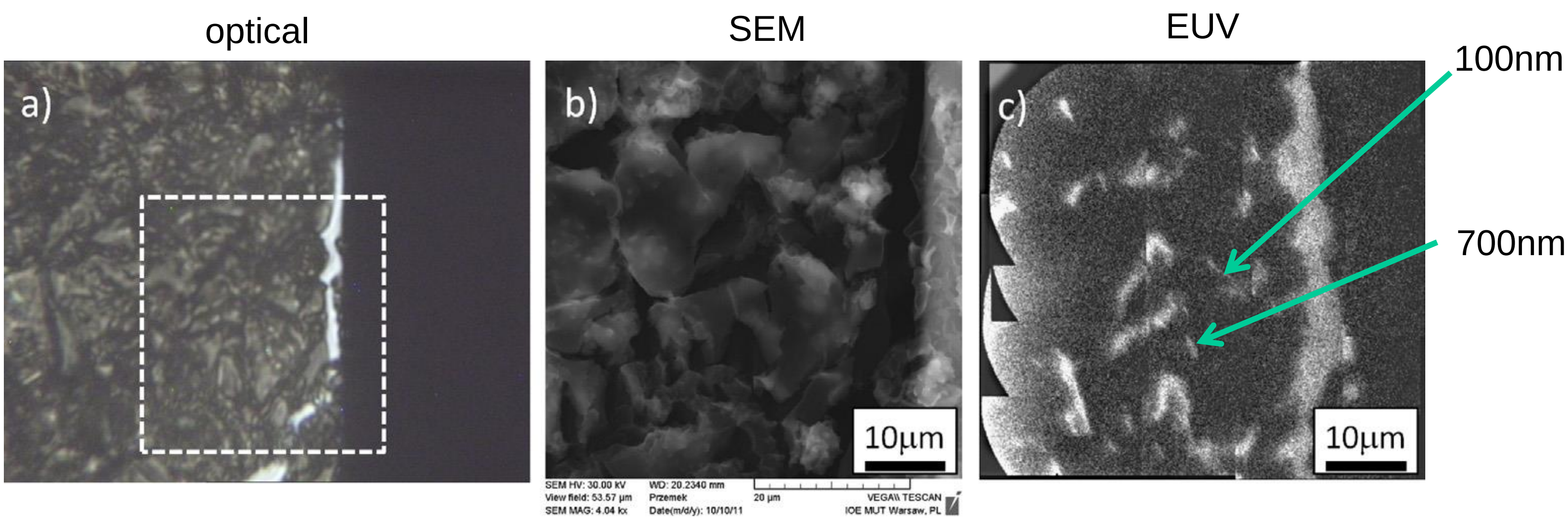


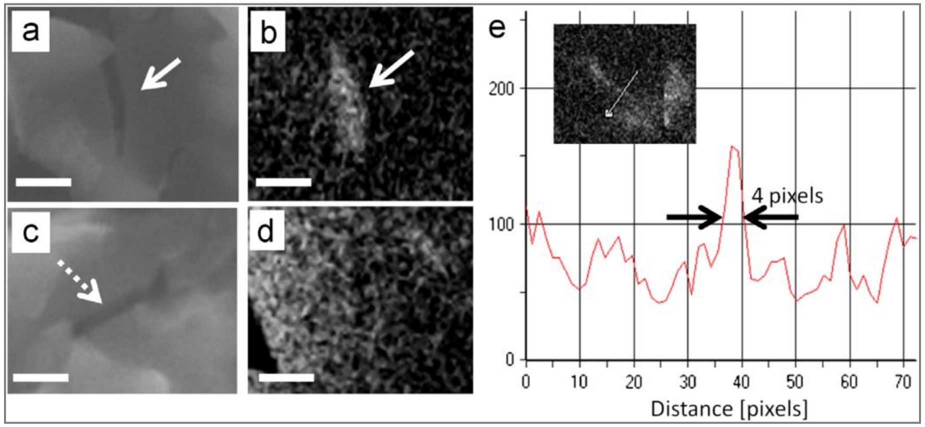
Collaboration with Prof. D. Elbaum – Institute of Physics PAS

P. Wachulak et al. *Rad. Phys. Chem.* ***93*** *(2013) 54*

Imaging of nanostructures: thin films

15nm thick silicon nitride membrane coated with salt crystals





✓Transparent regions with thickness <100nm (cracks, holes, etc.)

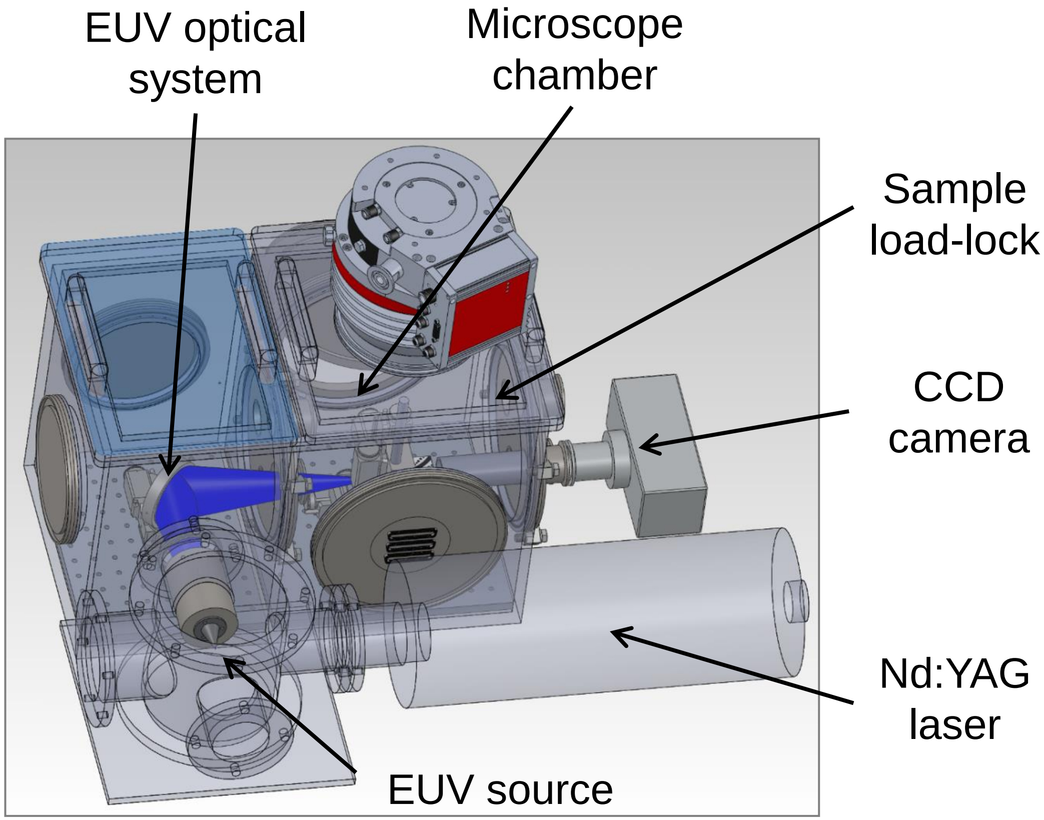
✓ 100nm features are visible

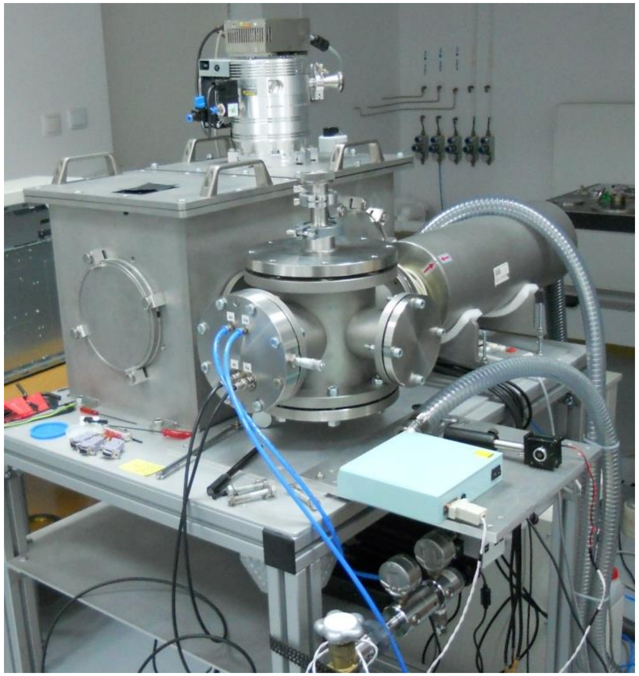
Collaboration with the Biophysics Department, CTU, Prague and the Institute of Physics PAS, Warsaw

P. Wachulak et al. *Rad. Phys. Chem.* ***93*** *(2013) 54*

EUV nanoimaging

Compact EUV microscope with a laser plasma source





P. Wachulak

LIDER 2012 Mikroskop EUV

EXTATIC

Doctoral Programme

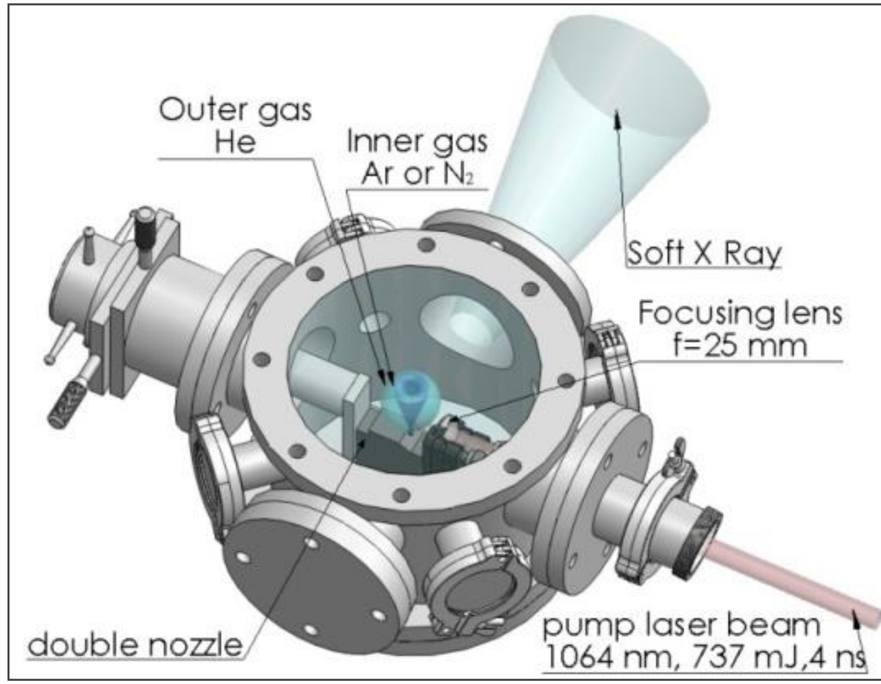
Alfio Torrisi - Italy

Laser plasma soft X-ray source

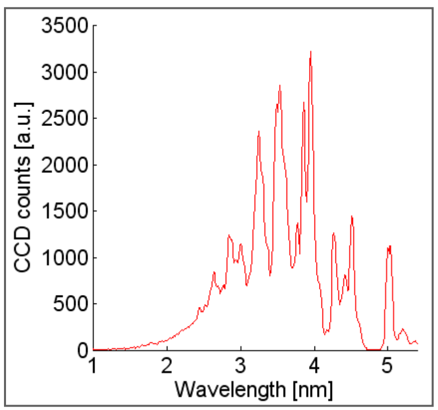
„Water window"

Laser parameters
0.8J, 4ns, 10Hz

Gas (argon or neon) pressure
10 bar



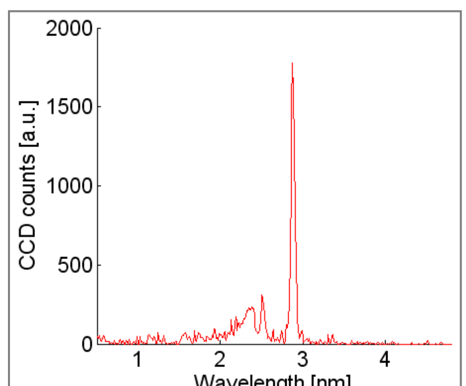
Argon



Wavelength range
2.5-4nm
Photon number in 4π
3.5×10^{14} /pulse

Photon energy in 4π
28.1mJ/pulse

Nitrogen



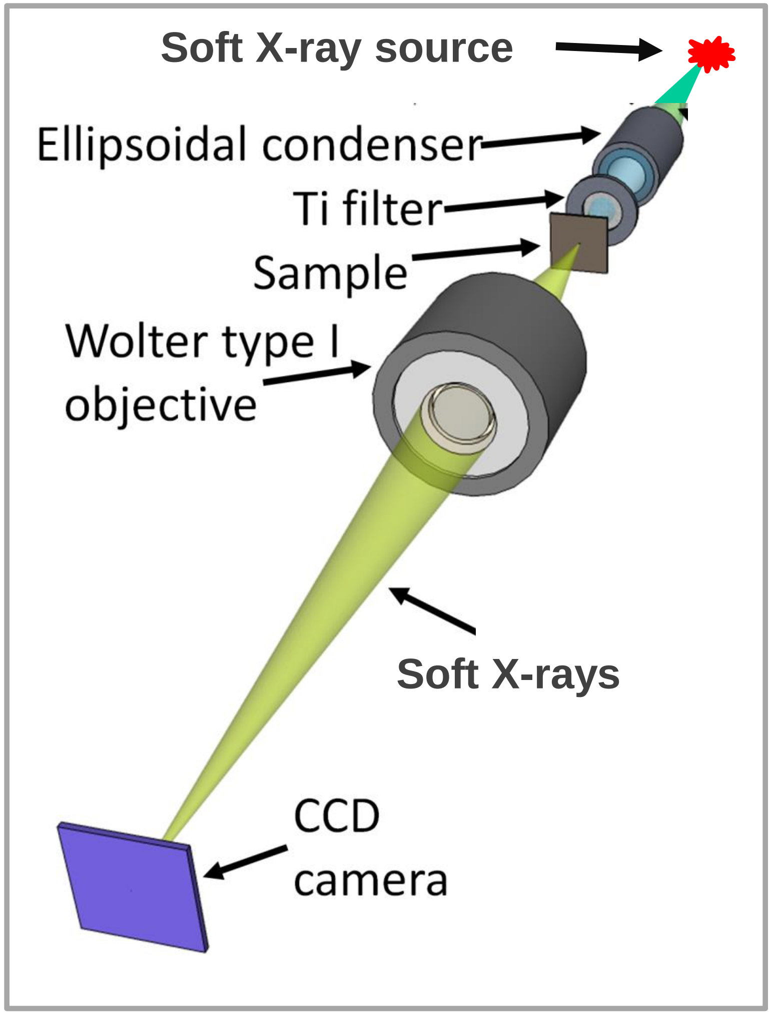
Wavelength
2.88nm
Photon number in 4π
5.6×10^{13} /pulse

Photon energy in 4π
3.9mJ/pulse

P. Wachulak et al. *Nucl. Instr. Meth. B* ***268*** *(2010) 1692*

Soft X-ray microscopy in the 'water window'

Soft X-ray microscope based on grazing incidence optics



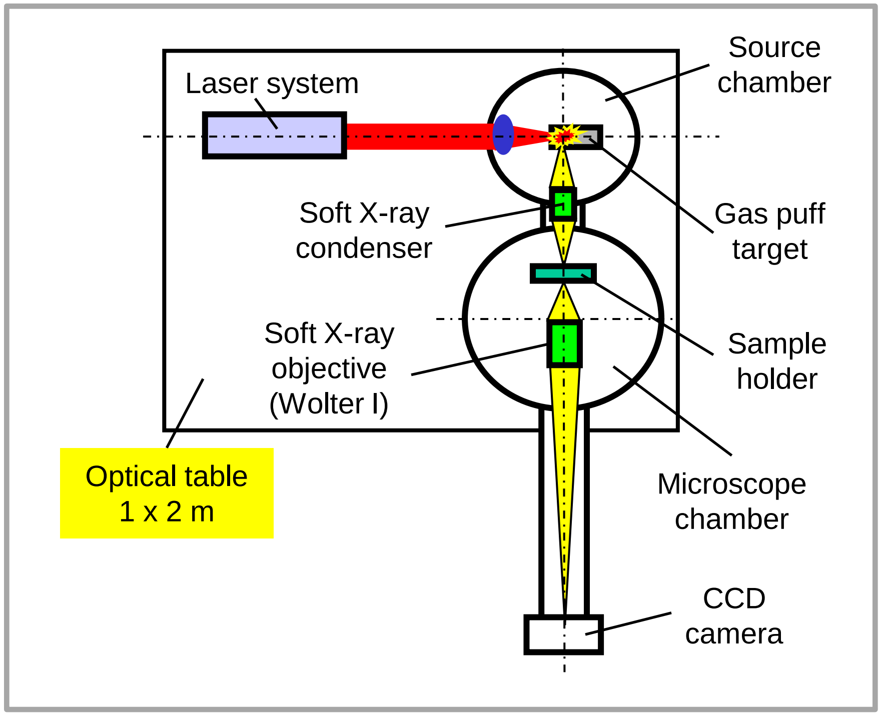
Condenser
axisymmetrical ellipsoid mirror*

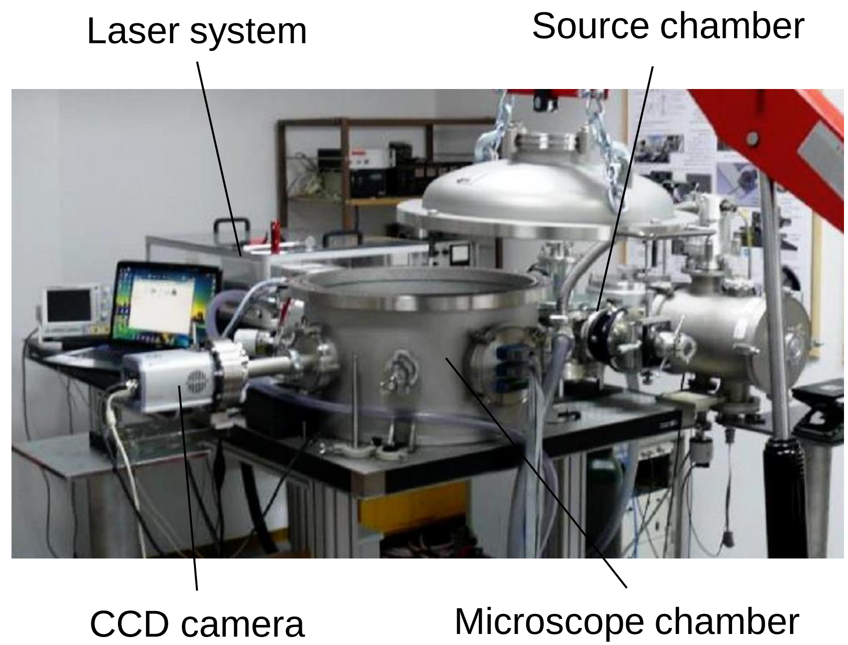
Objective
Wolter type axisymmetric ellipsoid/hyperboloid mirror**

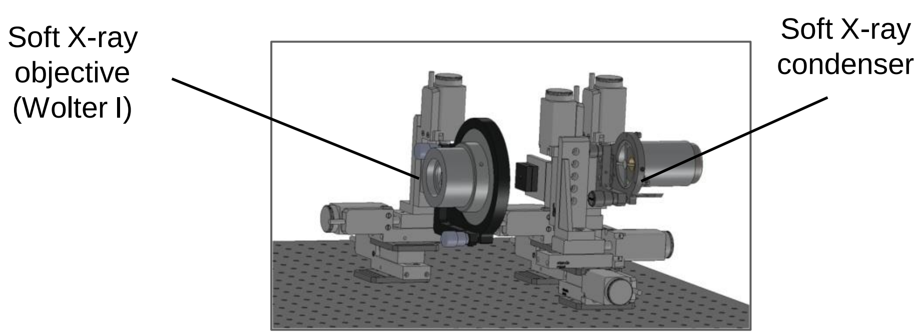
** Rigaku Inc. (Prof. L. Pina)*
*** Astronomical Institute of the ASCR and Czech Technical Univ. (Prof. R. Hudec)*

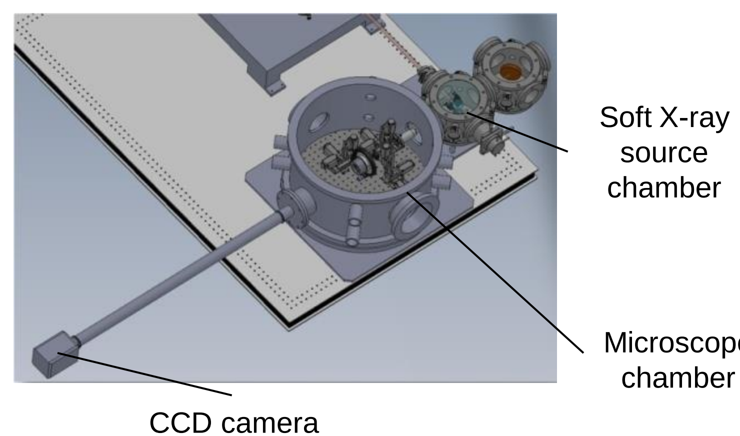
Soft X-ray microscopy in the ‘water window’

Desk-top soft X-ray microscope



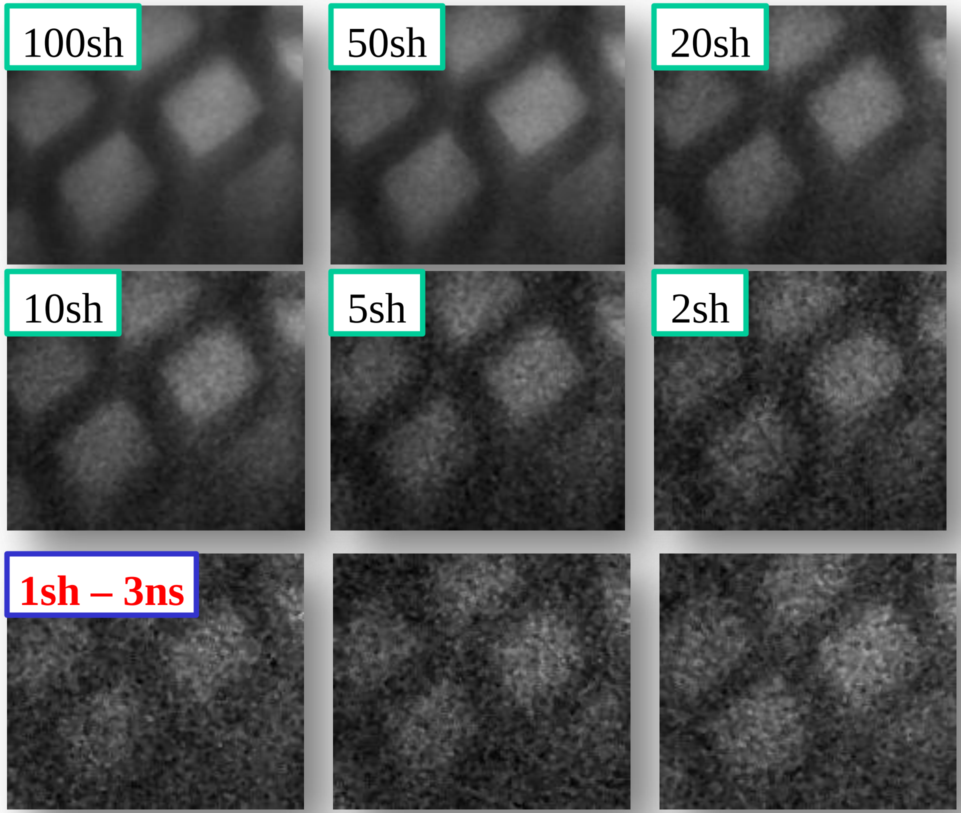






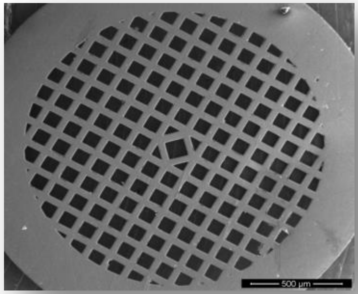
Soft X-ray microscopy images

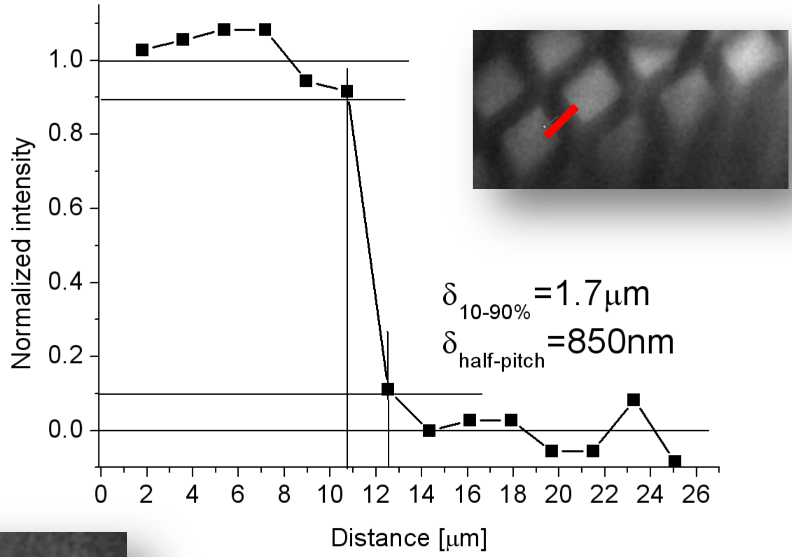
λ=2.88nm (N_2 plasma), Ti filter 200nm



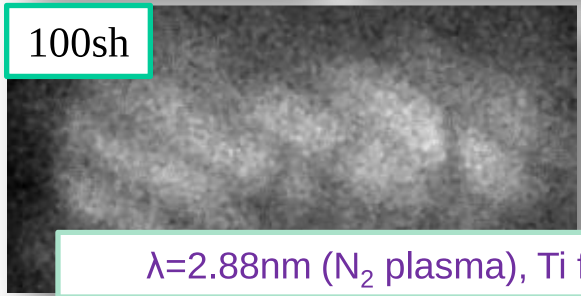
50 µm

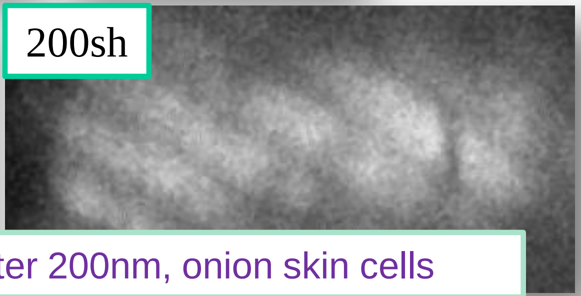
Test object Cu mesh





Half-pitch spatial resolution **~0.85 µm**



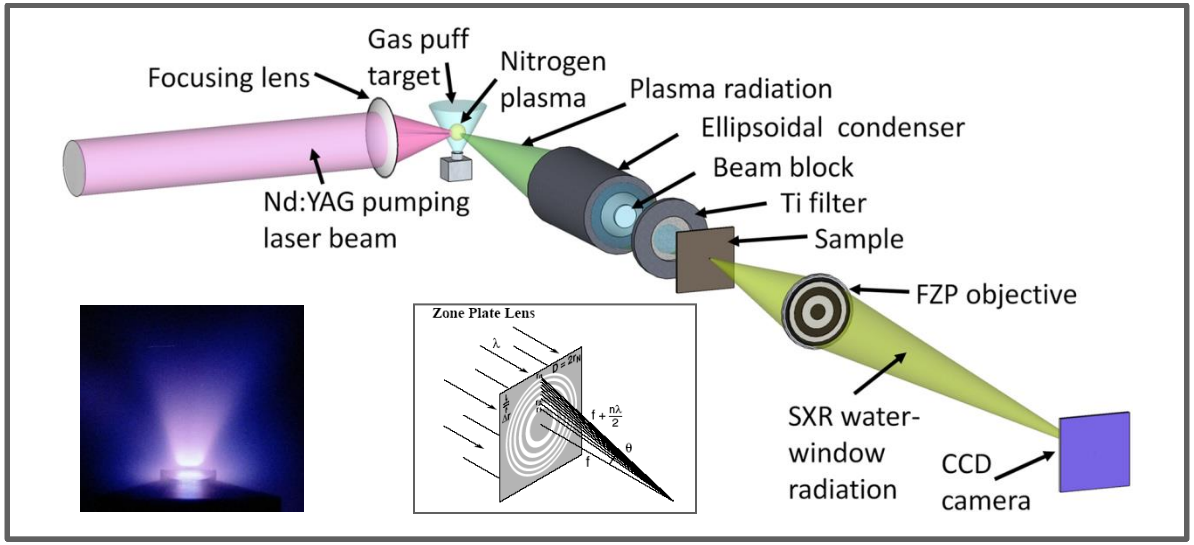


λ=2.88nm (N_2 plasma), Ti filter 200nm, onion skin cells

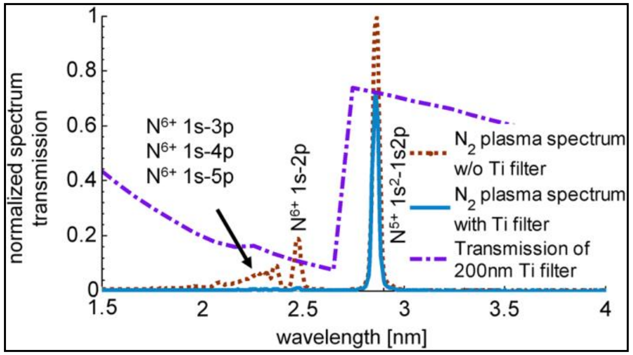
P. Wachulak et al., *NIMB **311** (2013) 42*

Soft X-ray microscopy in the ‘water window’

Desk-top soft X-ray microscope with a Fresnel zone plate



Soft X-ray spectrum



Soft X-ray images

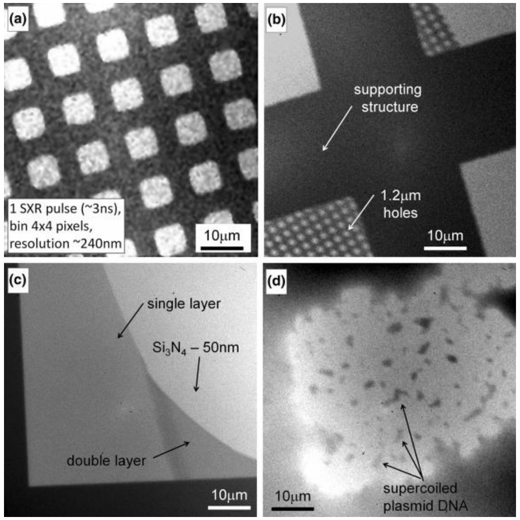
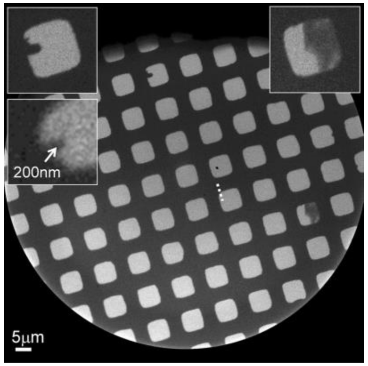
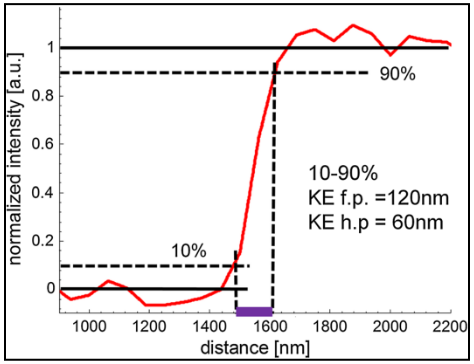


Image of the copper #2000 mesh obtained in the water window. Exposure equals **100 soft X-ray pulses/10 s**, FOV—120 × 120 μm^2.

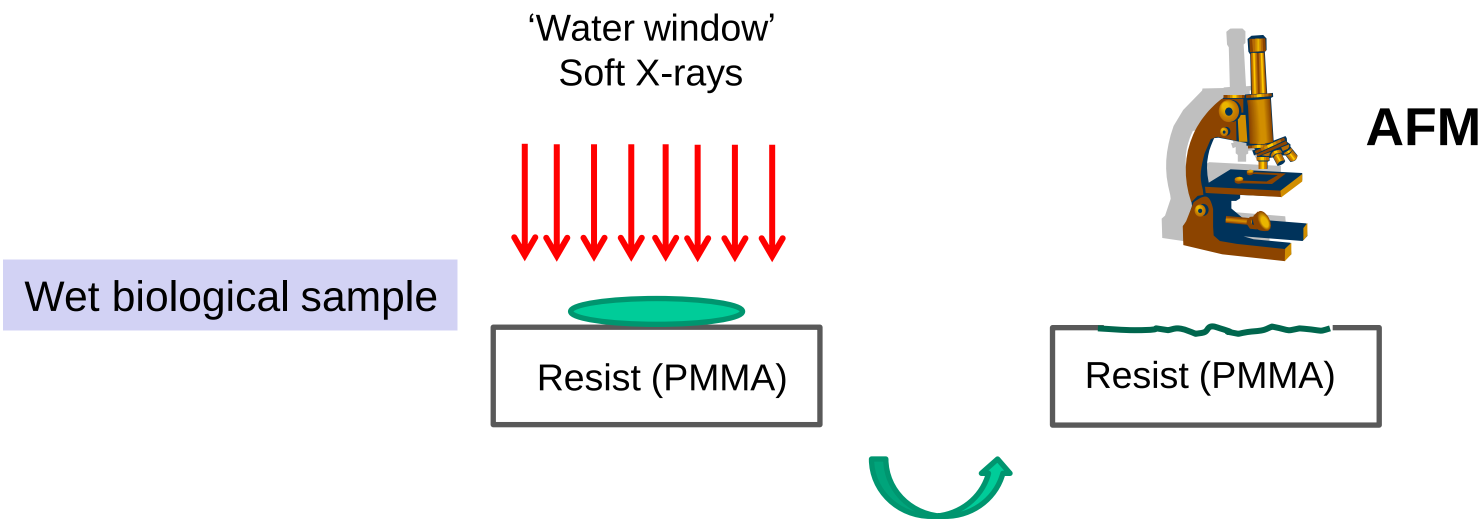


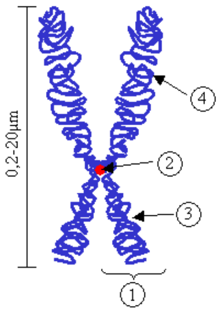


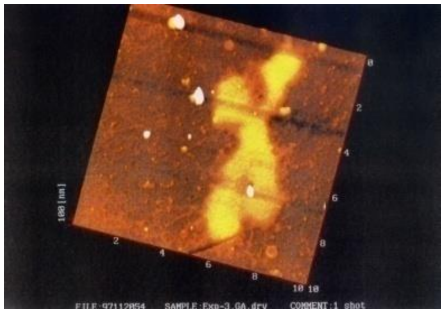
Spatial resolution ~60 nm

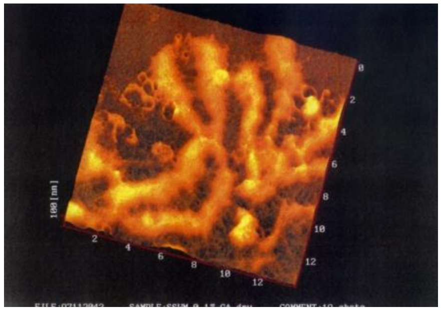
P.Wachulak et al.., Appl. Phys. B 118, 573-578 (2015)

Soft X-ray contact microscopy





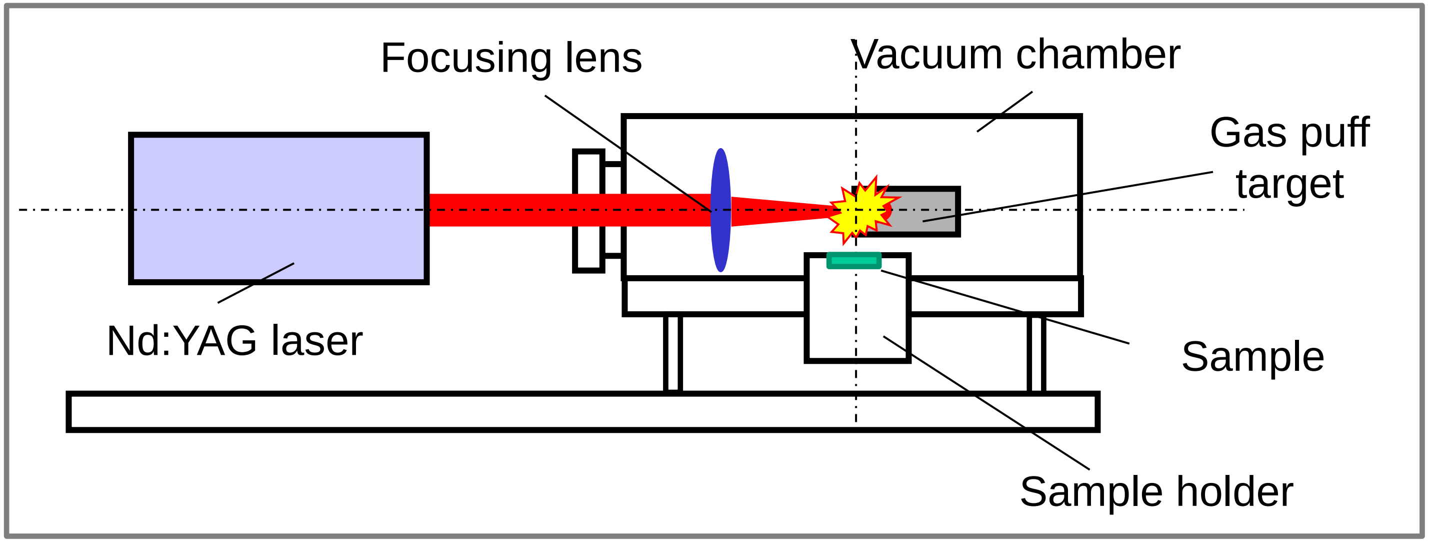




Y.Kinjo, M.Watanabe, H.Fiedorowicz, H.Daido, E.Yanase, S.Fujii, E.Sato, K.Sinohara
Fine structure of human chromosomes observed by x-ray contact microscopy
coupled with atomic force microscopy, J. Phys.IV **104** (2003) 313

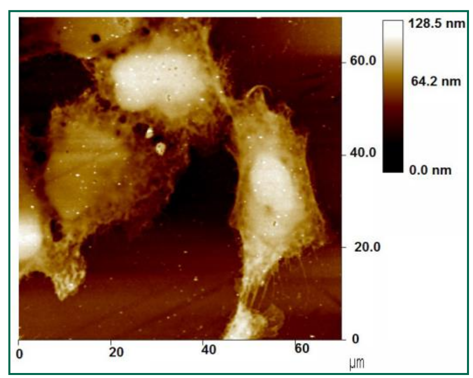
Soft X-ray contact microscopy

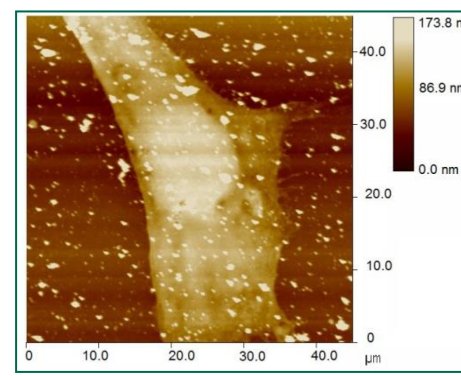
Schematic of the soft X-ray contact microscope



Doctoral Programme

Mesfin Ayele - Ethiopia



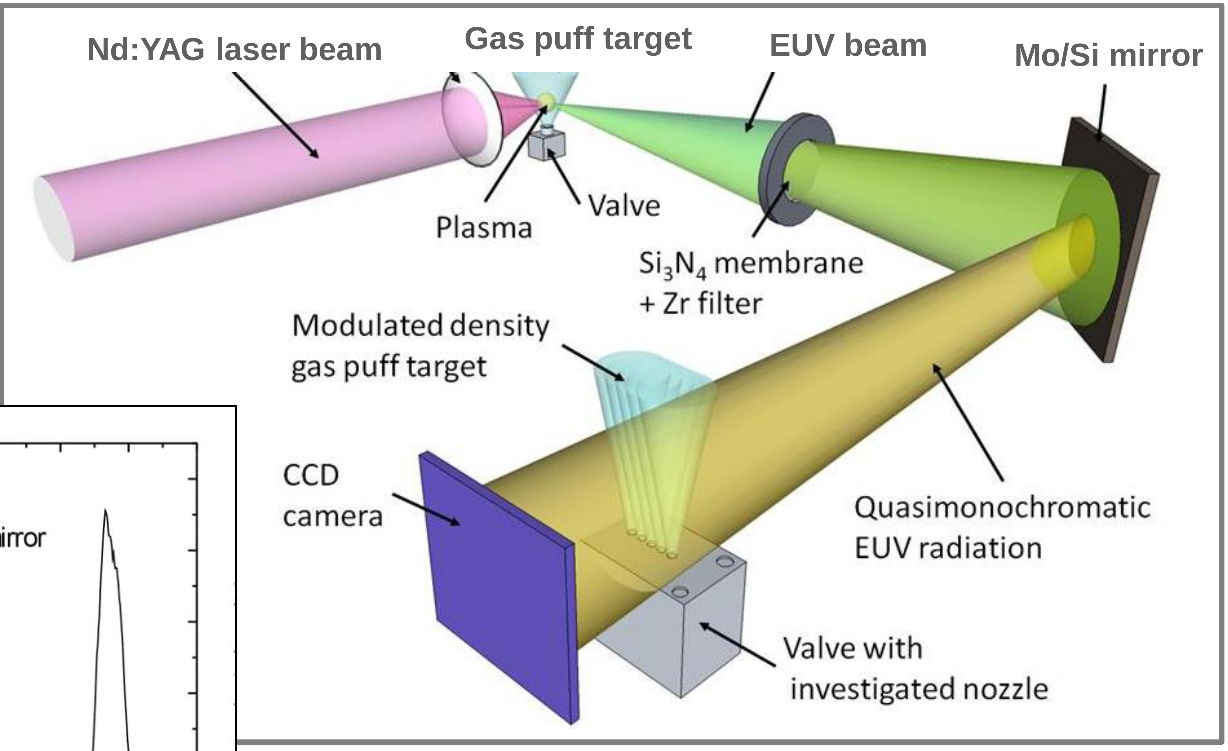


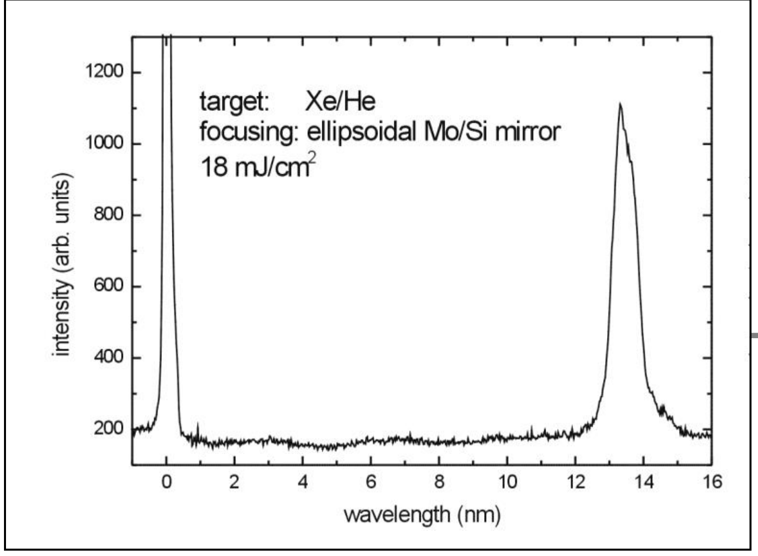
M. Ayele et al. Proc. SPIE (2015) - accepted

Collaboration with Institute of Nuclear Physics, Cracow

EUV pulsed radiography

Schematic of the EUV radiography setup





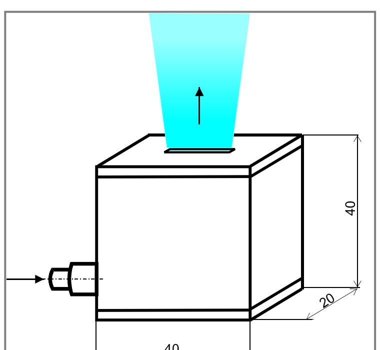
13.5nm

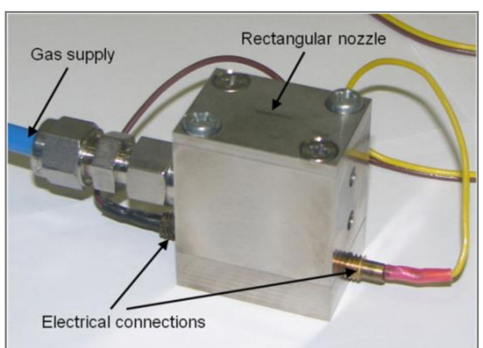
Quasi-monochromatic EUV backlighter from Xe ions emission spectrally selected using Mo/Si mirror and Zr filter

EUV pulsed radiography

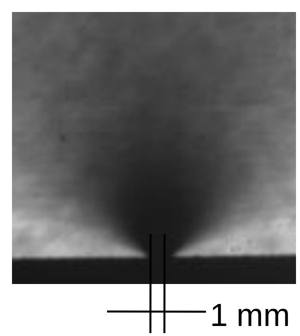
Experimental setup for EUV radiography

Characterization of elongated gas puff targets for HHG and EA

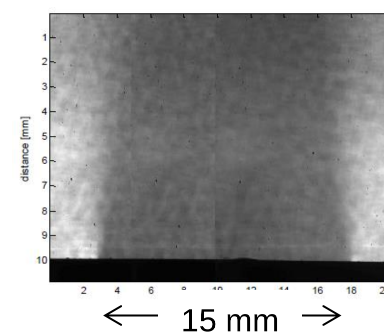




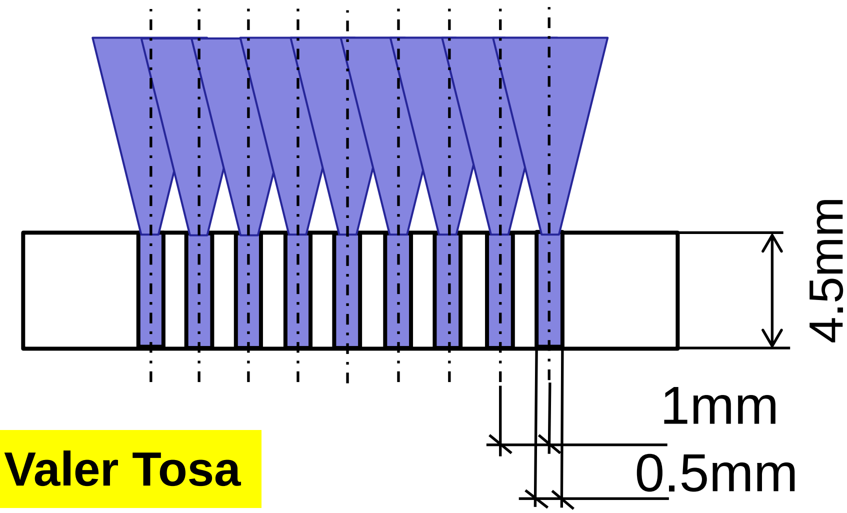
Front view



Side view

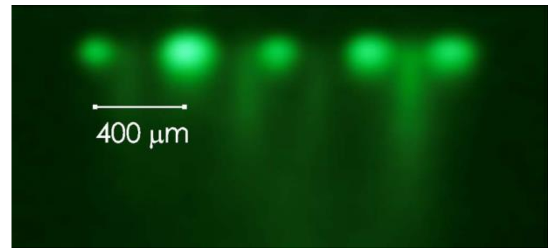


Multi-jet gas puff target for HHG

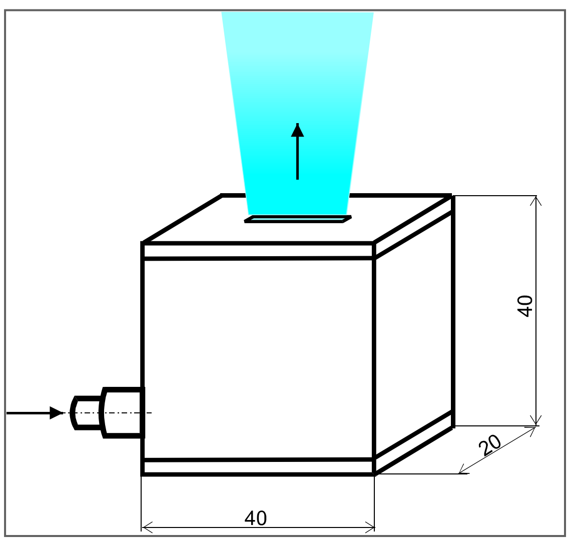


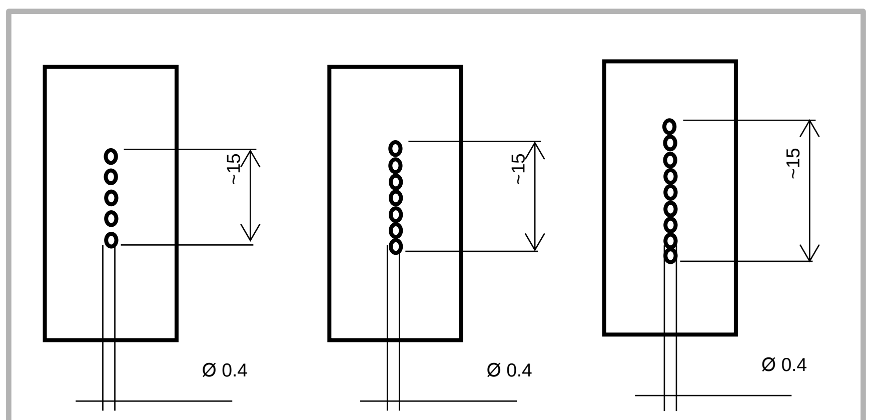
Valer Tosa

A. Pirri, C. Corsi, M. Bellini, Enhancing the yield of high-order harmonics with an array of gas jets, Phys. Rev. A **78** (2008) 011801R



High-order harmonic generation region in the 5-hole gas jet





Schematic of the nozzles

Nozzles

Characterization of multi-jet targets

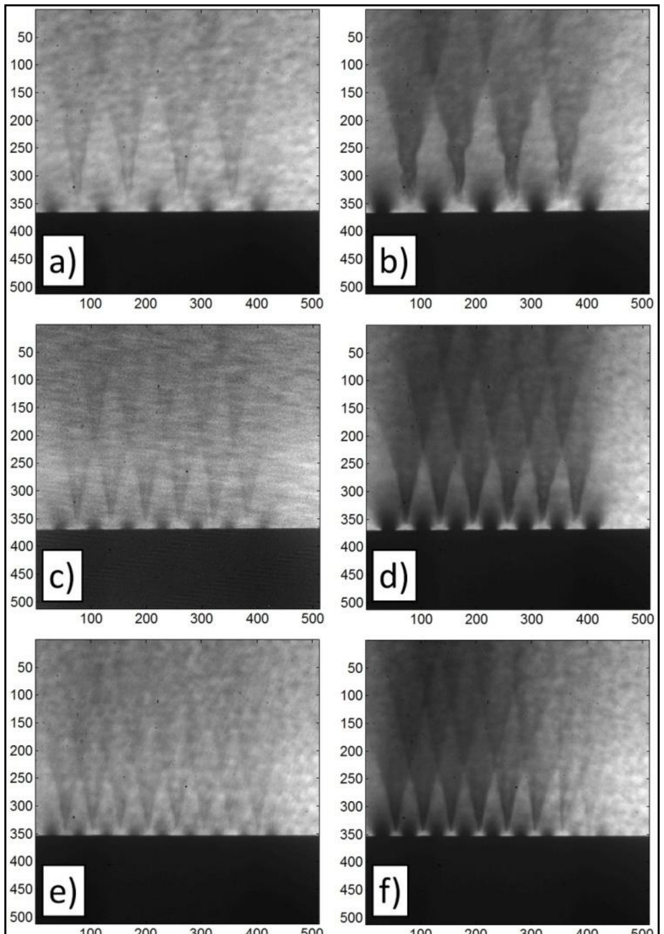
EUV shadowgrams of the multi-jet gas puff targets produced with 5, 7 and 9 orifice nozzles at low (2bar) and high (10bar) backing pressures

2-D gas density map for the multi-jet target produced with the 7 orifice nozzle at the backing pressure of 4bar and gas density profiles for various distances from the nozzle

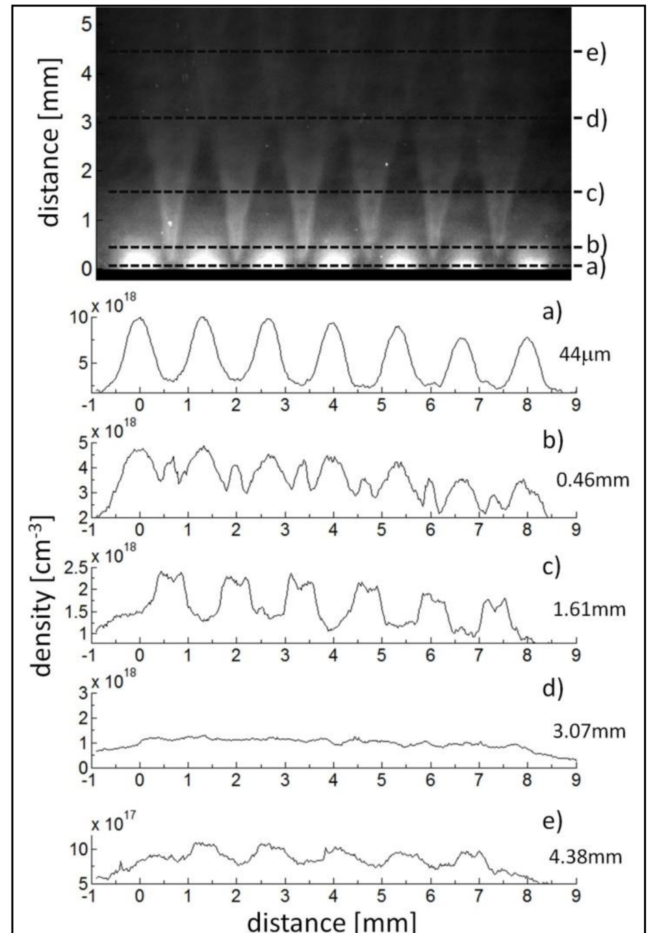
5 orifices

7 orifices

9 orifices



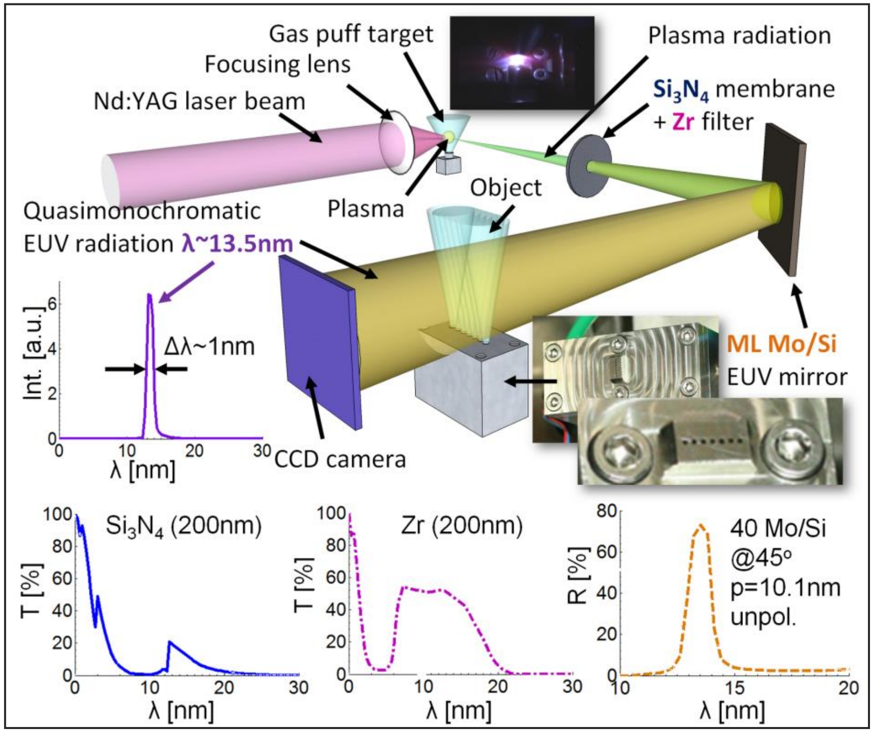
2bar 10bar



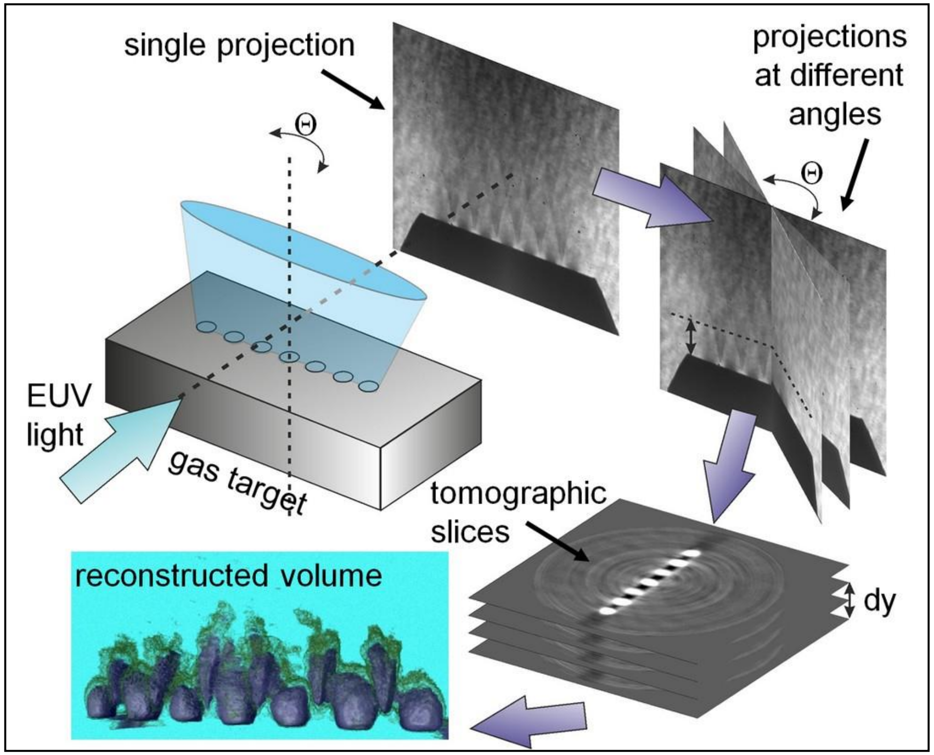
P.W. Wachulak, et al.,Nucl. Instr. Meth. B **285** (2012)102

EUV tomography of a multi-jet gas puff target

Schematical layout of the EUV tomography experiment



3-D reconstruction of the multi-jet gas puff target

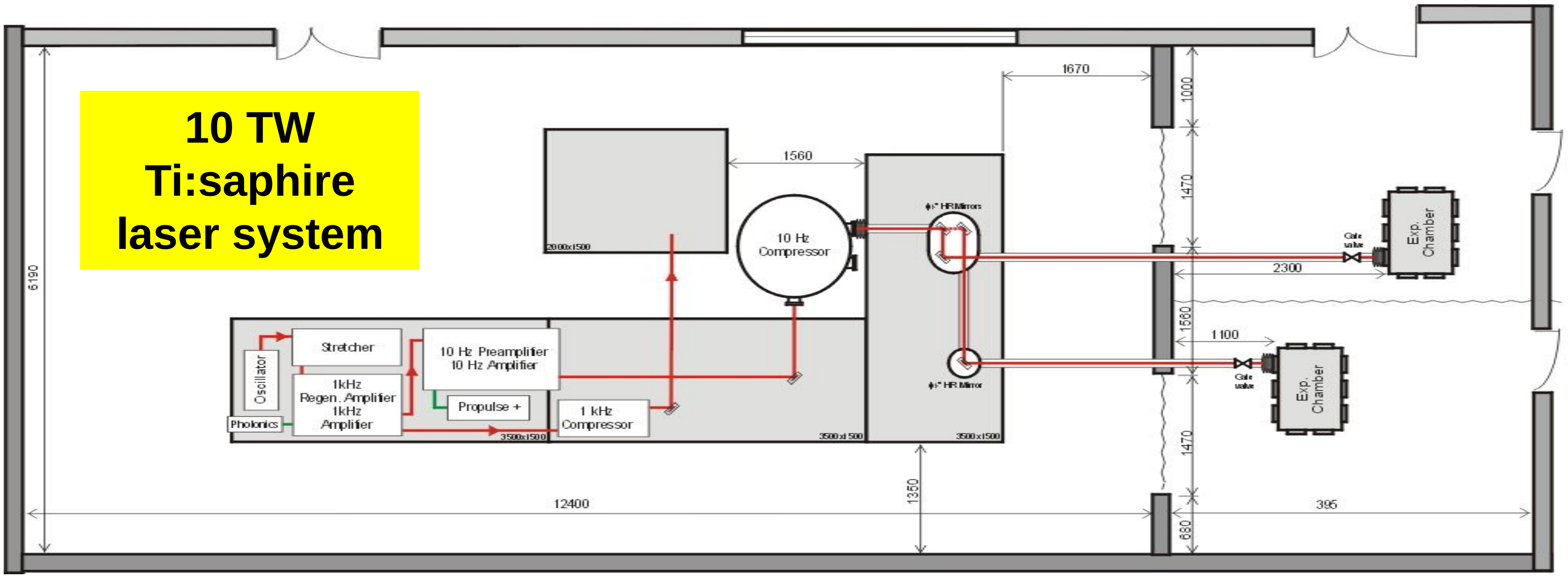


P. Wachulak, et al., Optics Letters **39** (2014) 532

Collaboration with Institute of Electrical Engineering, Bratislava

High-intensity femtosecond laser system

- generation of coherent EUV radiation (HHG)
- generation of ultra-short X-ray pulses

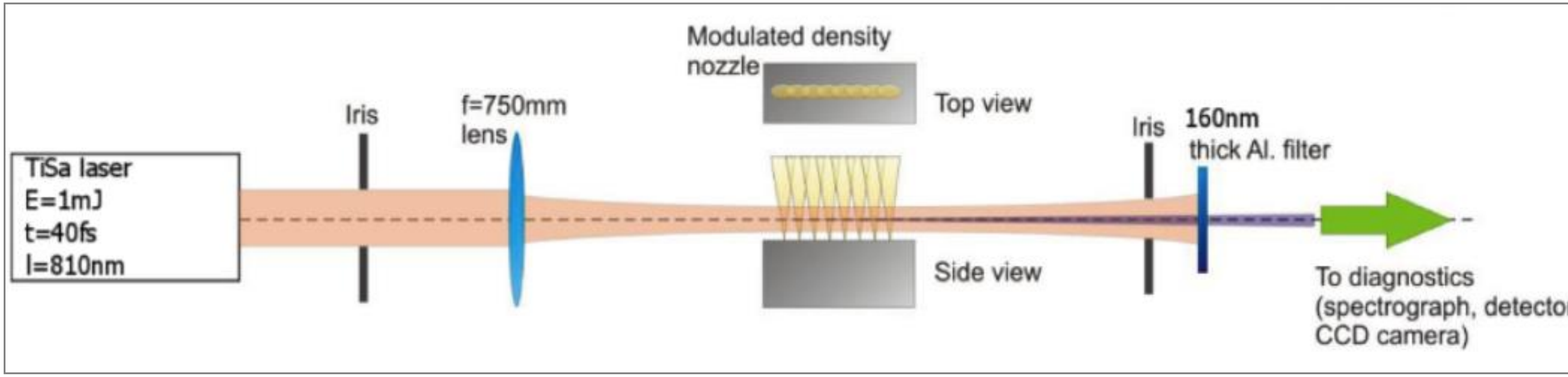


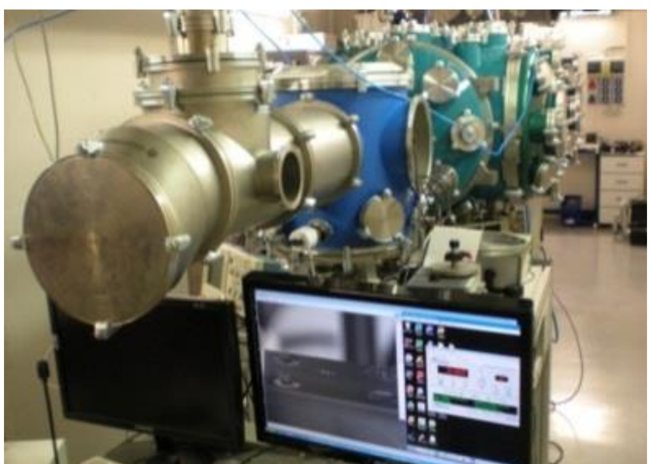
PULSAR 1kHz part
- pulse energy > 3mJ
- pulse duration < 50fs

PULSAR 10Hz part
- pulse energy 750mJ
- pulse energy > 500mJ (compr.)
- pulse duration < 50fs

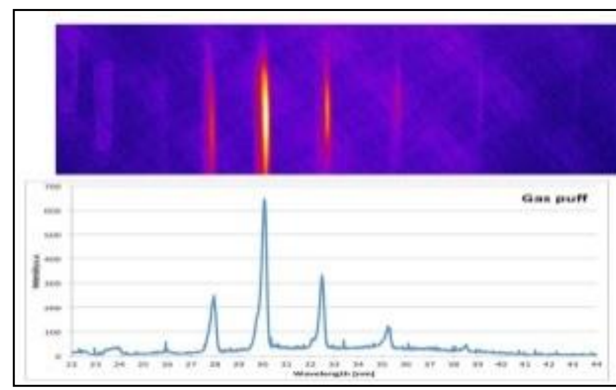
Experiments on HHG using multi-jet targets

HHG experiments at PALS, Prague





High-order harmonic
generation region
in the 9-hole gas jet



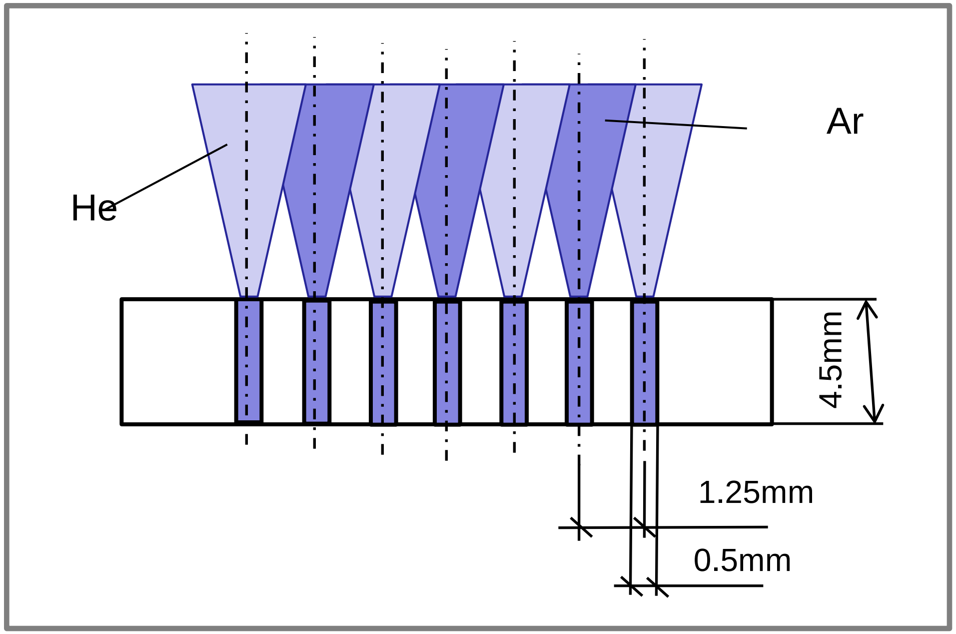
Doctoral Project

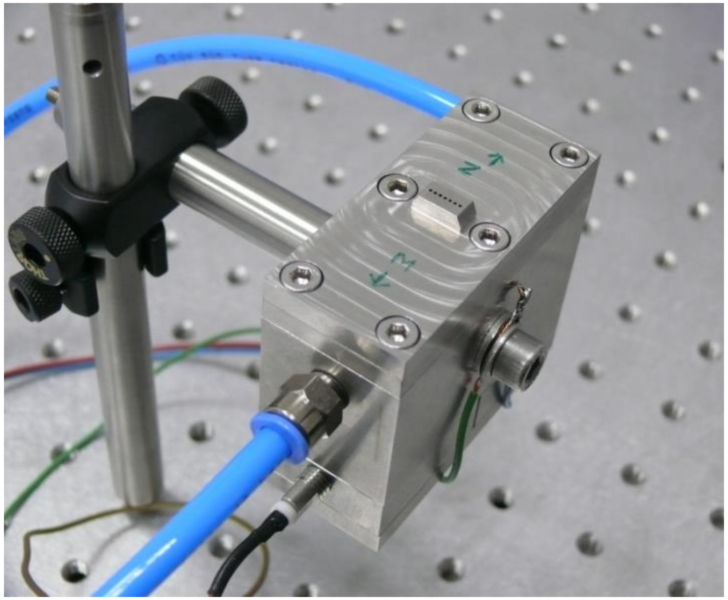
Tomasz Fok

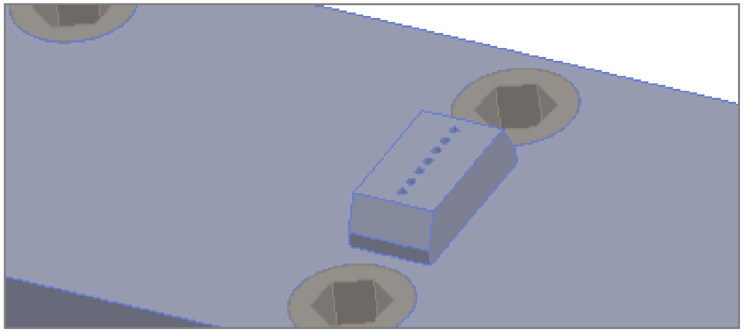
T. Fok at al. Photonics Letters of Poland (2014)

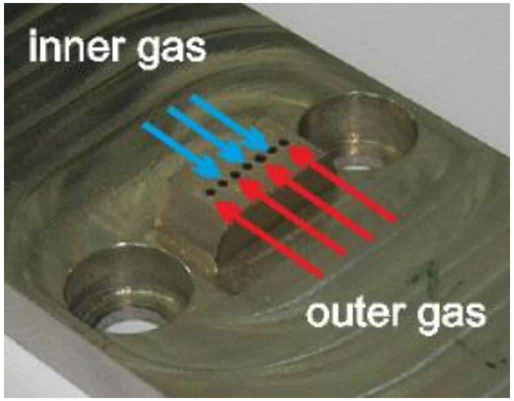
Dual gas multi-jet gas puff target

A. Willner, et al., Coherent control of high harmonic generation via dual-gas multijet arrays, Phys. Rev. Lett. 1**07** (2011) 175002







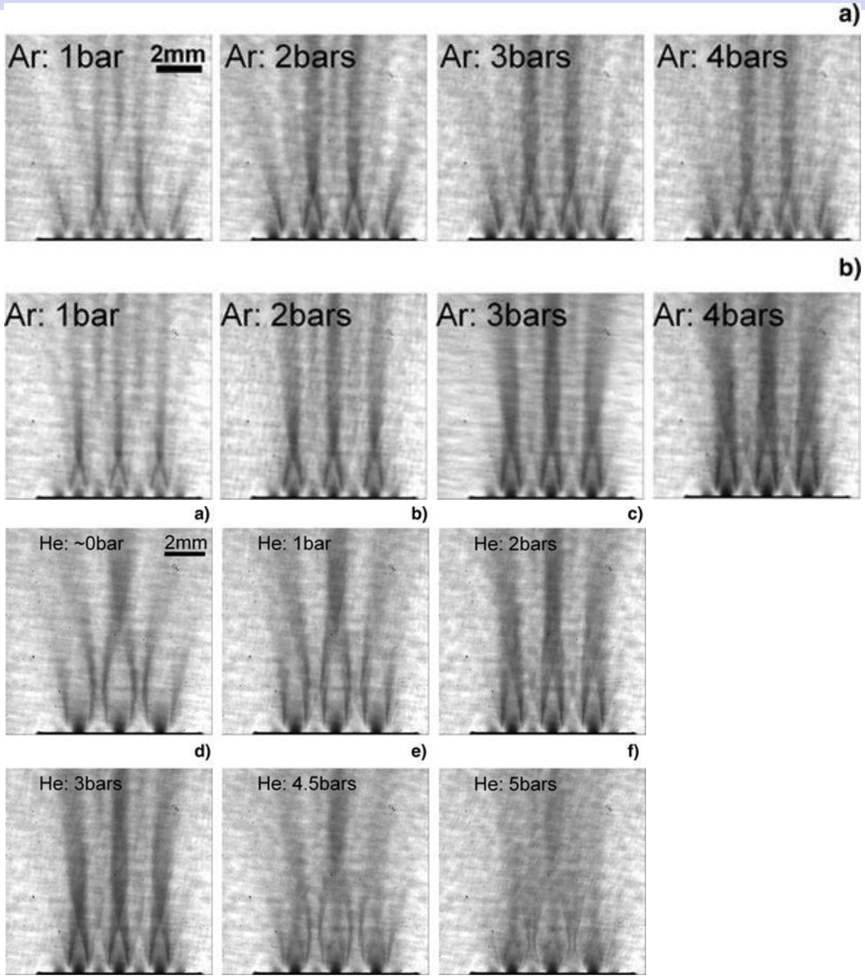


Characterization of dual gas multi-jet targets

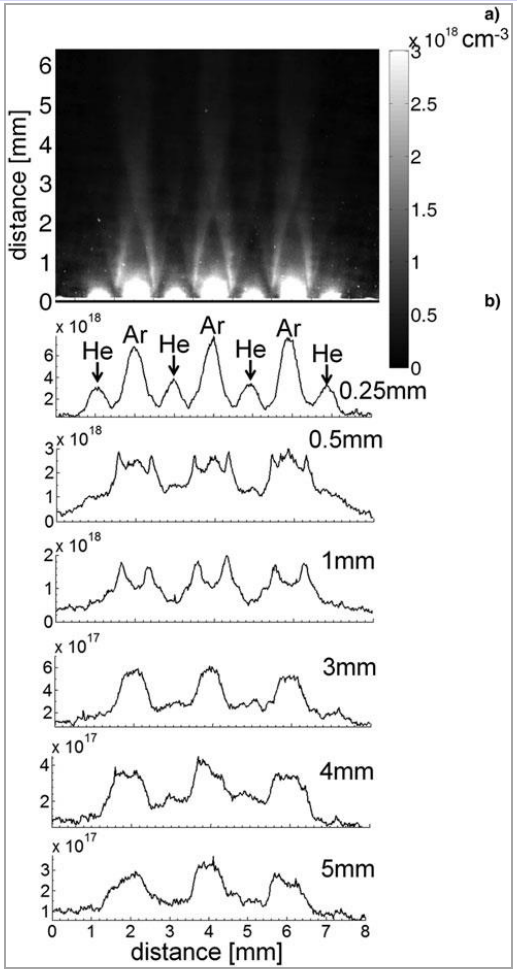
EUV shadowgrams of the He/Ar targets

He 4bar

Ar 4bar



Gas density contours and profiles



P. Wachulak, Laser & Particle Beams **31** (2013) 219

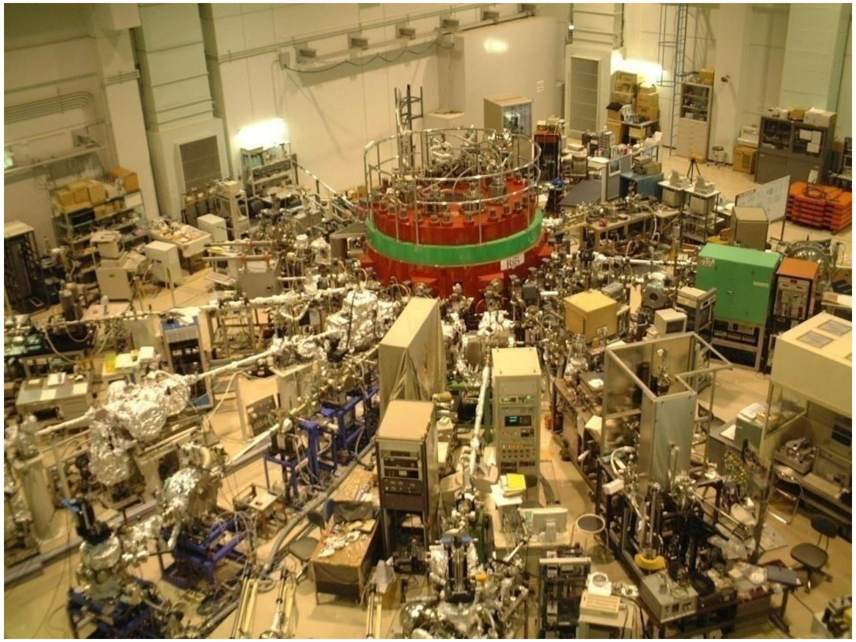
Processing polymers with soft X-ray/EUV photons

• **Ritsumeikan University Synchrotron Research Center**

Synchrotron Aurora:
- electron energy: 575 MeV
- critical wavelength: 1.5 nm
- 3×10^{17} ph/s/cm^2 at a sample surface

Non-thermal ablation of PTFE demonstrated:
- ablation depth: 240μm
- aspect ratio: 11

Advantages (as compared to LIGA):
- dry process,
- EUV radiation preferred (smaller facility and no high-contrast masks are required).



Y. Zhang, T. Katoh, M. Washio, H. Yamada, S. Hamada, *Appl. Phys. Lett.*, ***67*** *(6) (1995) 872*

Processing polymers with EUV photons

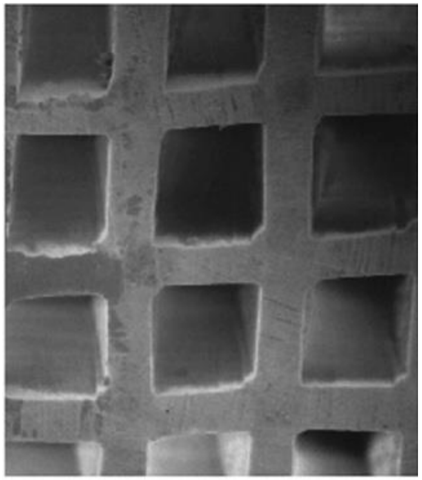
- **UVSOR at the Institute for Molecular Science, Okazaki National Research Institute, Japan**

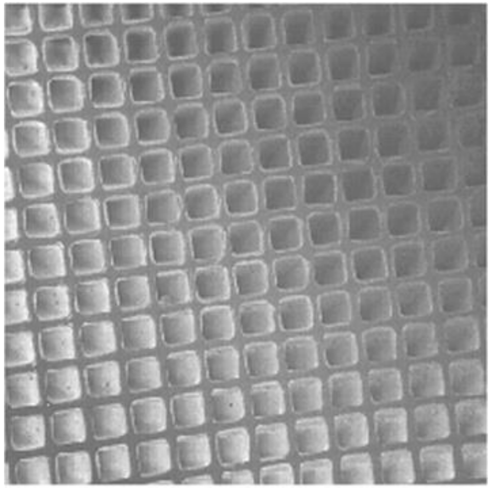
National Institutes of Natural Sciences
分子科学研究所
Institute for Molecular Science

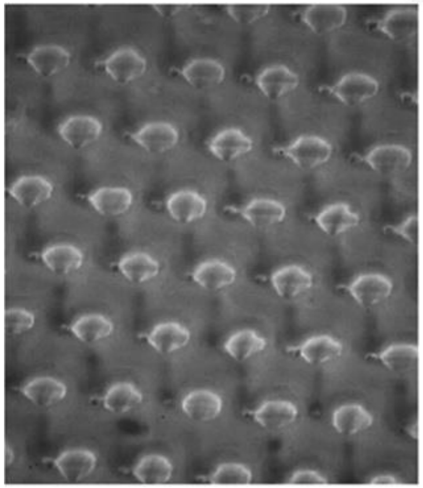
UVSOR Facility.

High Aspect Ration Micromachining of PTFE (Teflon)

- 1-mm-thick Teflon
- aspect ratio: 50
- 10 nm wavelength







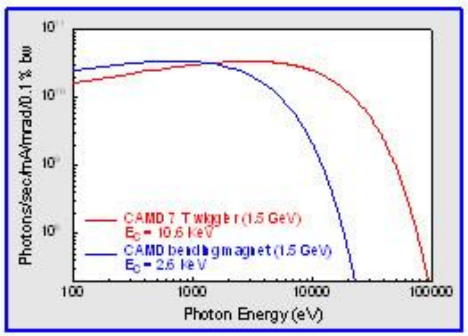
M. Inayoshi *et al. J. Vac. Sci. Technol. B* ***17*** *(1999) 949*

Processing polymers with soft X-rays

The J. Bennett Johnston, Sr.
CAMD
Center for Advanced Microstructures and Devices

Synchrotron CAMD Louisiana State Univ:

- electron energy: 1.5 GeV
- critical energy: 2.5 keV
- integrated power density 35 mW/horizontal cm

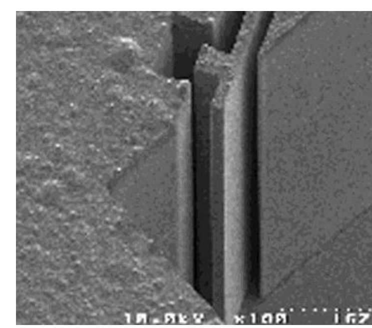


CAMD Experimental Hall

Soft X-ray ablation of heated Teflon

Non-thermal x-ray ablation of PTFE demonstrated:

- ablation rate: **40µm/h**
- strong temperature dependent
- photochemical changes of x-ray irradiated samples

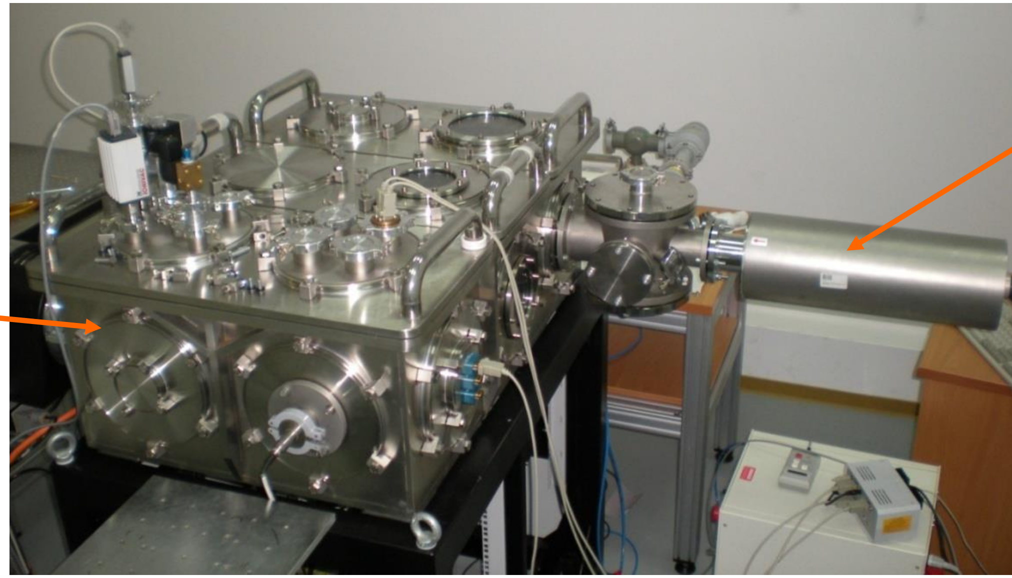


M. Feldman, G. S. Lee, D. Noel, C. Khan Malek, R. Bass
*J. Vac Sci. Technol. B., **18** (6) (2000) 2976*

Laser plasma EUV source for processing

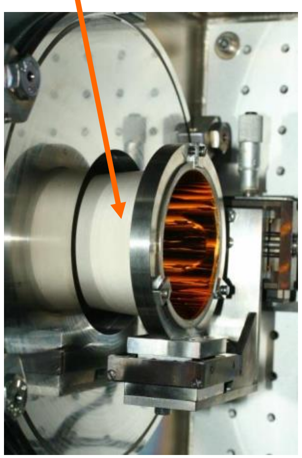
EUREKA

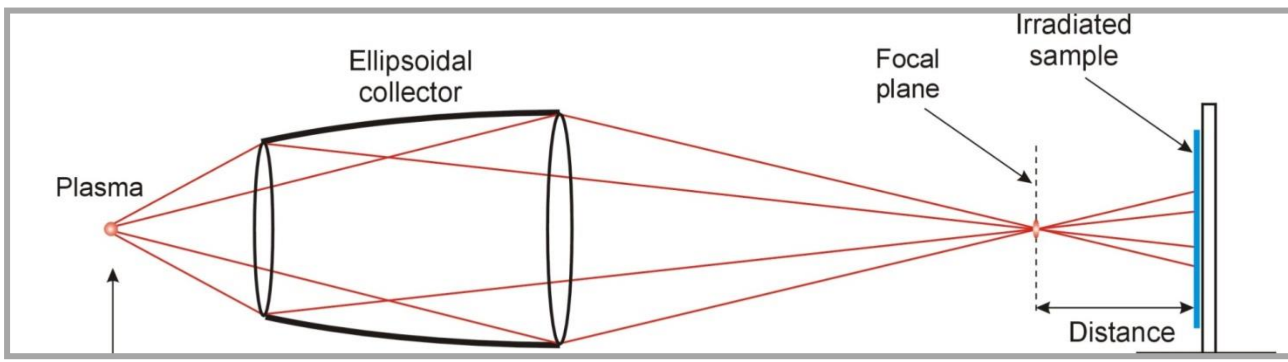
Vacuum chamber

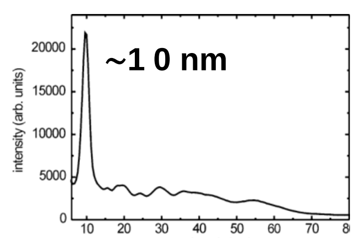


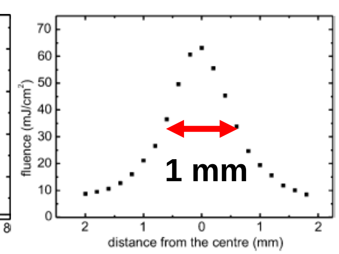
Nd:YAG laser

Ellipsoidal EUV collector









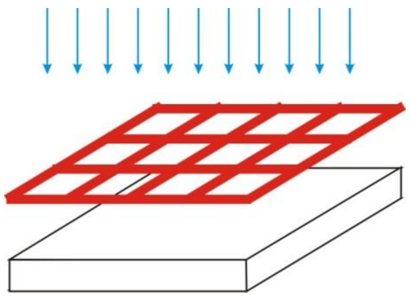
100 mJ/cm^2

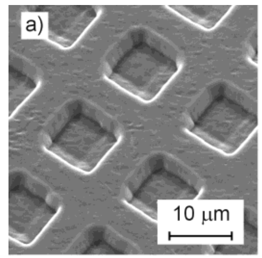
A. Bartnik *et al.* Appl.Phys. B (2012)

EUV microstructuring of polymers

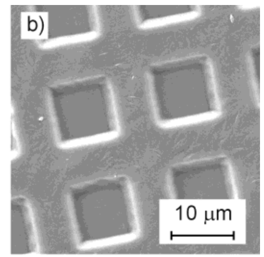
SEM images of polymer foils irradiated through a metallic grid

Schematic of exposure

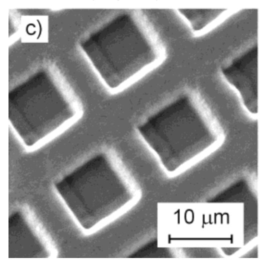




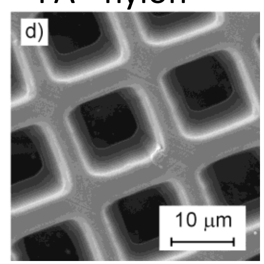
PVDF



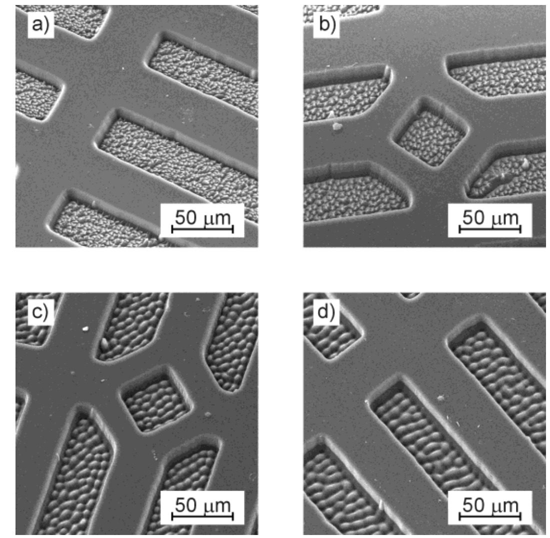
PA - nylon



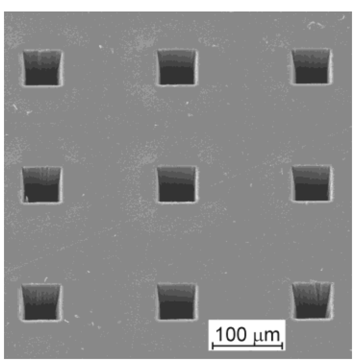
PMMA

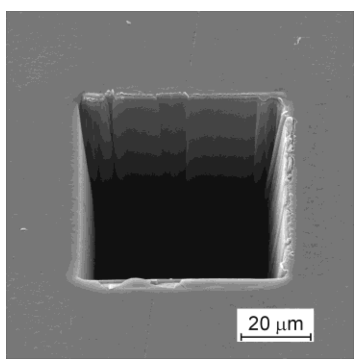


PMMA



PET, 300 EUV pulses, temperature:
a) 25^{0}C, b) 100^{0}C, c) 150^{0}C, d) 180^{0}C





PVDF – fluoropolymer having piezo- and piroelectric properties, chemically resistant, difficulties in laser and X-ray micromachining. Easy EUV photoetching.

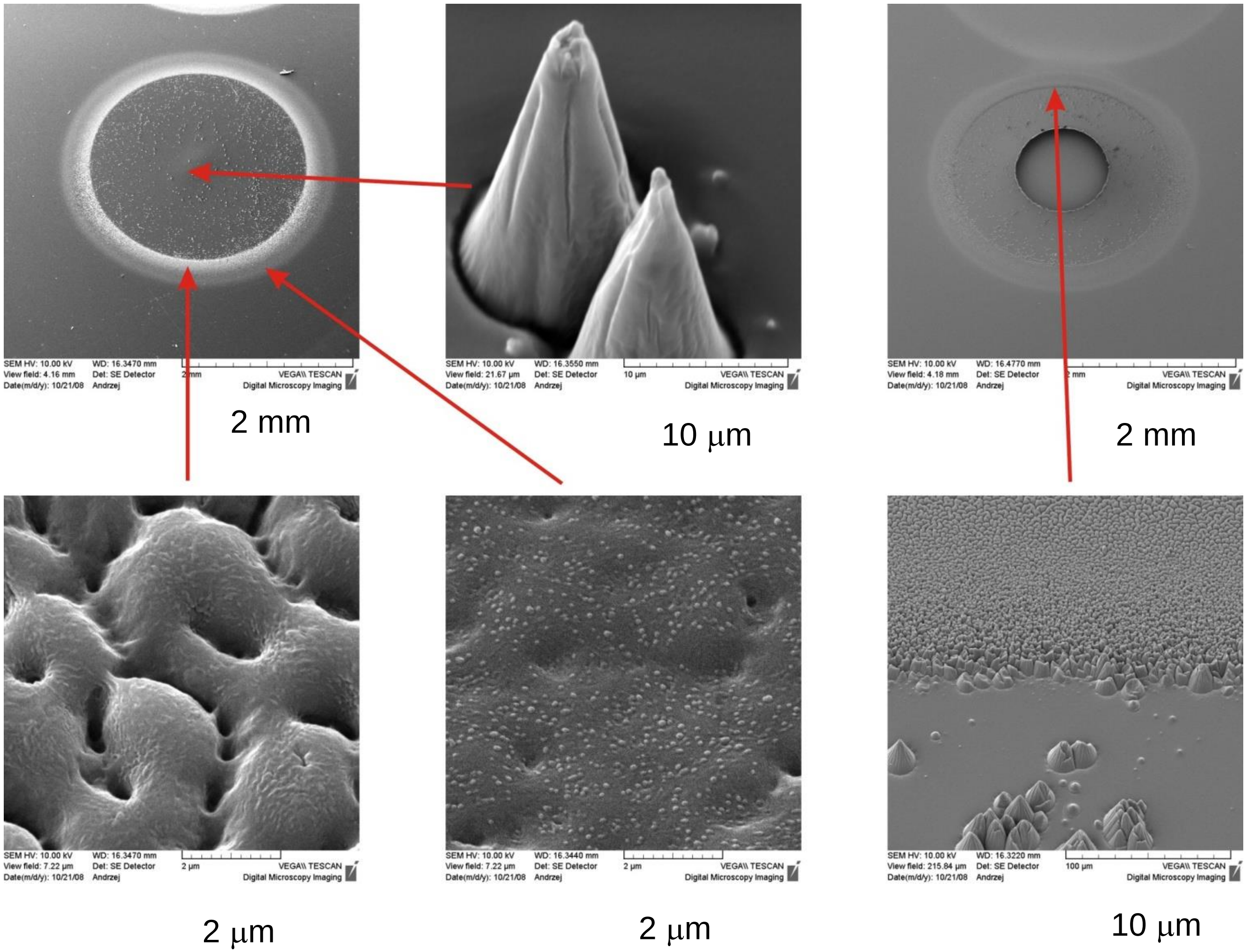
50 µthick PVDF foil – 1 min exposition time

Bartnik et al. *Appl. Phys.* 106, 551 (2012)

Polymethyl methacrylate (PMMA)

SEM images of PMMA irradiated in the focal plane of Mo-coated ellipsoidal collector, Xe plasma radiation, repetition rate 10 Hz

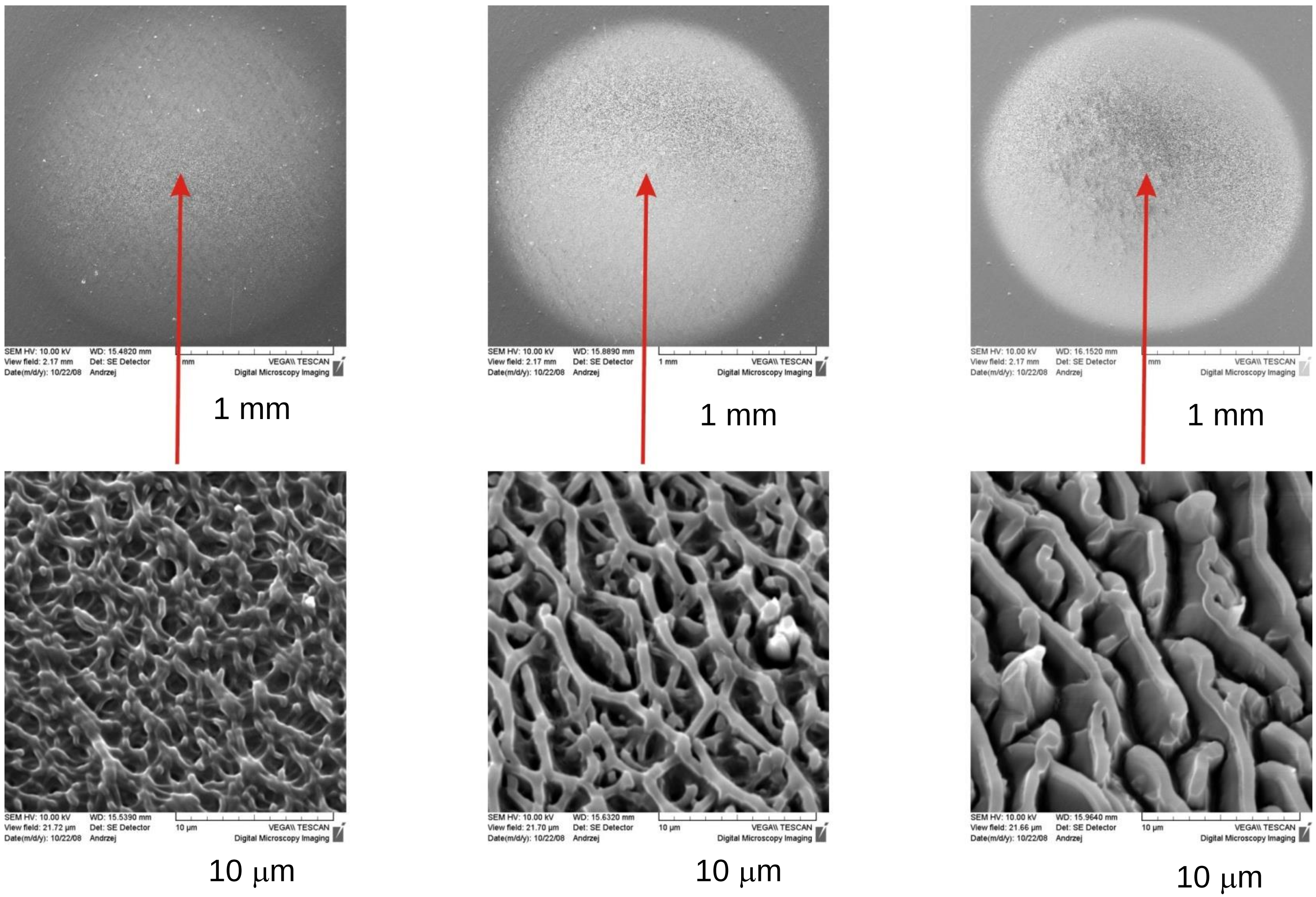
1 min exposure



2 min exposure

Polyvinyl fluoride (PVF)

SEM images of PVF irradiated 3 mm behind the focal plane of Mo-coated ellipsoidal collector, Xe plasma radiation, repetition rate 10 Hz



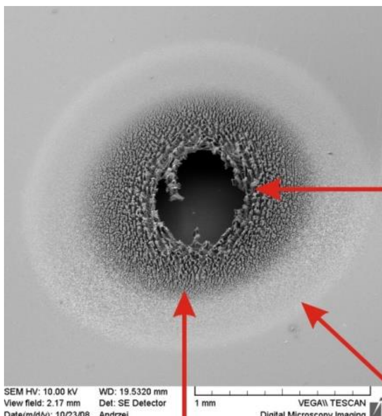
5 s exposure

10 s exposure

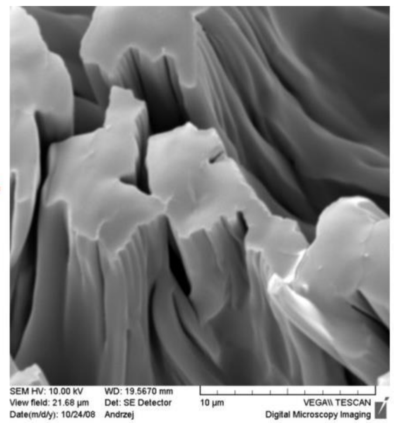
30 s exposure

Polystyrene (PS)

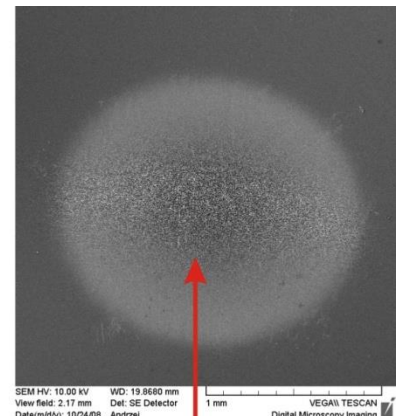
SEM images of PS irradiated in the focal plane of Mo-coated ellipsoidal collector, Xe plasma radiation, repetition rate 10 Hz



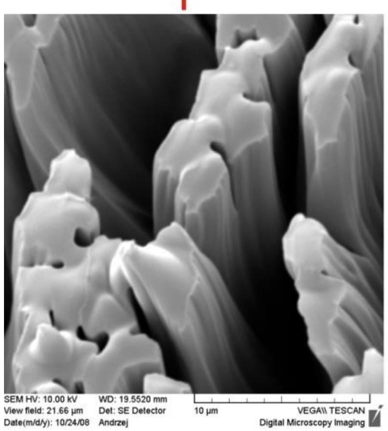
1 mm



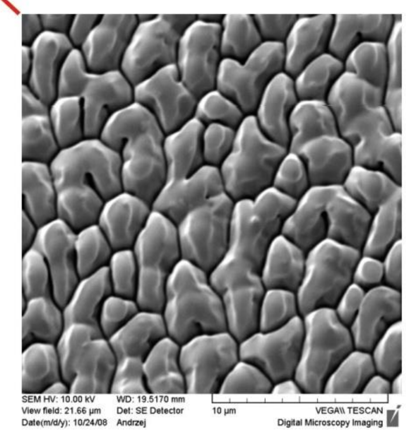
10 μm



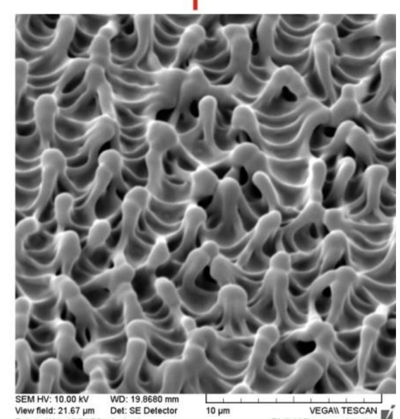
1 mm



10 μm



10 μm



10 μm

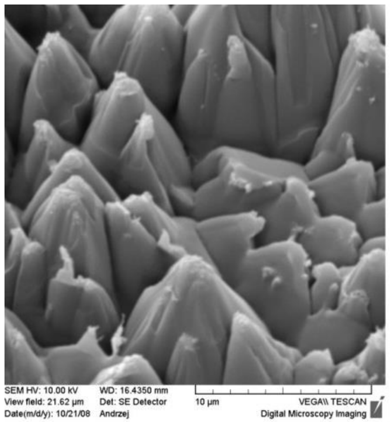
1 min exposure

2,5 s exposure

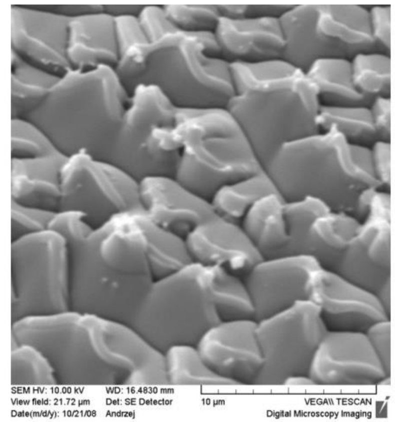
Polyethylene terephthalate (PET)

SEM images of PET irradiated behind the focal plane of Mo coated ellipsoidal collector, Xe plasma radiation, repetition rate 10 Hz

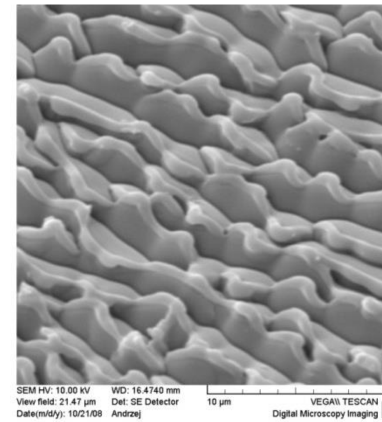
Central part



10 μm

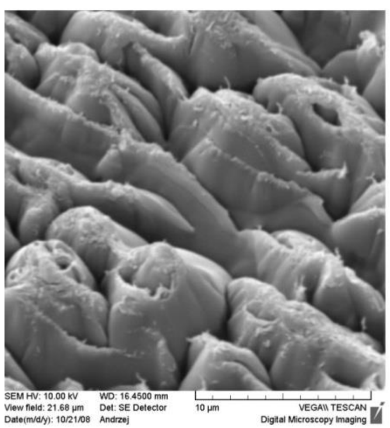


10 μm

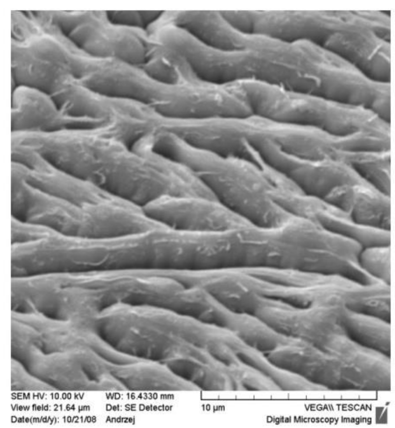


10 μm

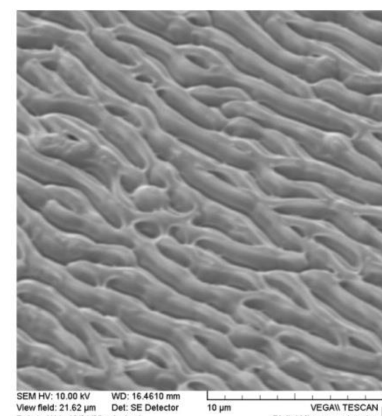
Close to an edge of the focal spot



10 μm



10 μm



10 μm

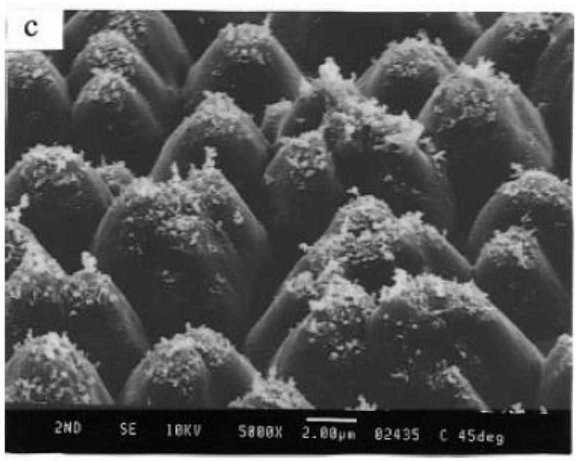
1 min exposure

30 s exposure

10 s exposure

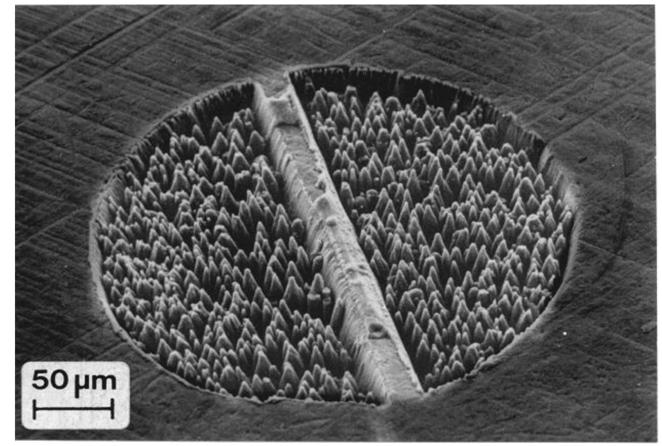
Surface modification with UV lasers

Polymer - KrF laser



T. Lippert et al. *Macromolecules* **29** (1996) 6301

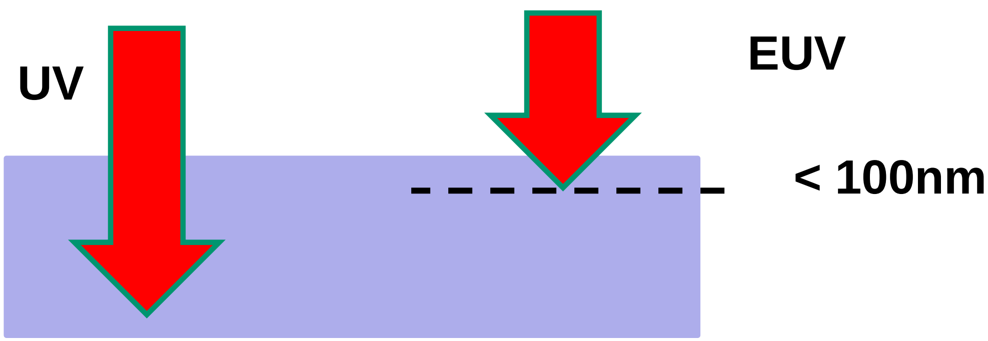
Si_3N_4 Ceramics – ArF laser



J. Heitz et al. *Appl. Phys*. **A 65**, 259 (1997)

Application in biomedicine – control biocompatibility

Degradation of bulk material by UV



Prof. Johannes Heitz

Applied Physics Linz

JOHANNES KEPLER UNIVERSITY LINZ
Research and teaching network

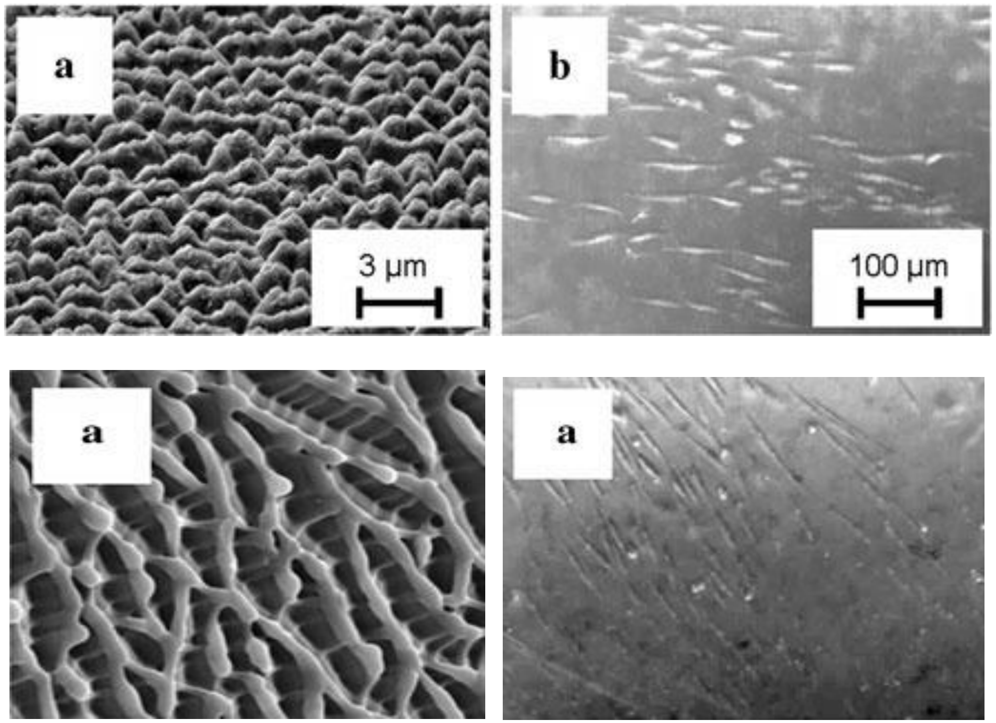
Biocompatibility control using EUV irradiation

• **Cultivation of CHO cells at PET**

Phase Contrast Microscope

UV irradiated

EUV irradiated



EUREKA

• good alignment of Chinese hamster ovary (CHO) cells along the direction of the walls was found,

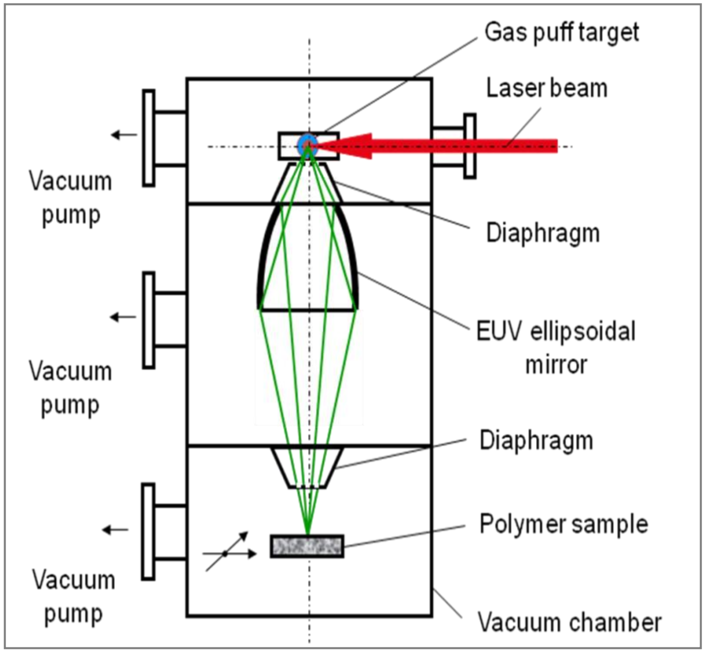
• CHO cells showed only bad adhesion at the irradiated surfaces and no alignment for samples irradiated with UV laser at 193 nm,

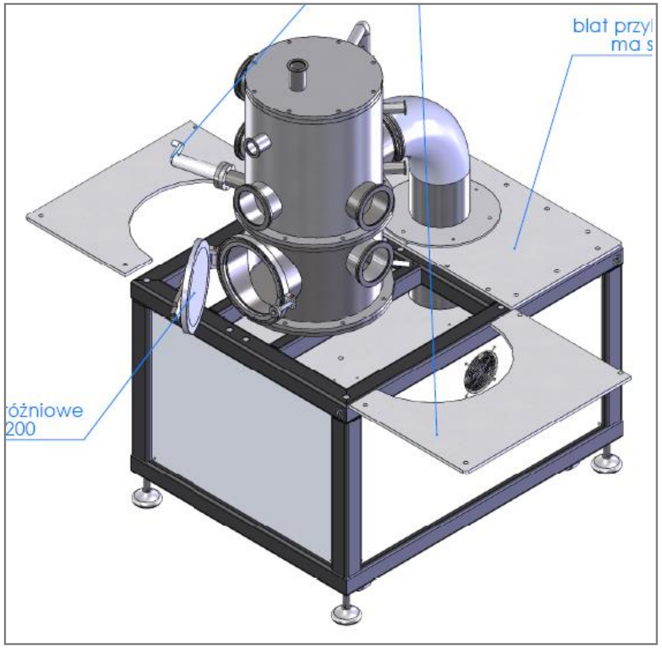
• chemical surface modification is **more pronounced for EUV irradiation.**

B. Reisinger *et al. Appl. Phys. A* **100** (2010) 511

Laser plasma EUV source for processing polymers

Laser plasma EUV source for processing polymers has been designed at **IOE** and was built in co-operation with **EKSPLA, RIGAKU and PREVAC** high-tech companies





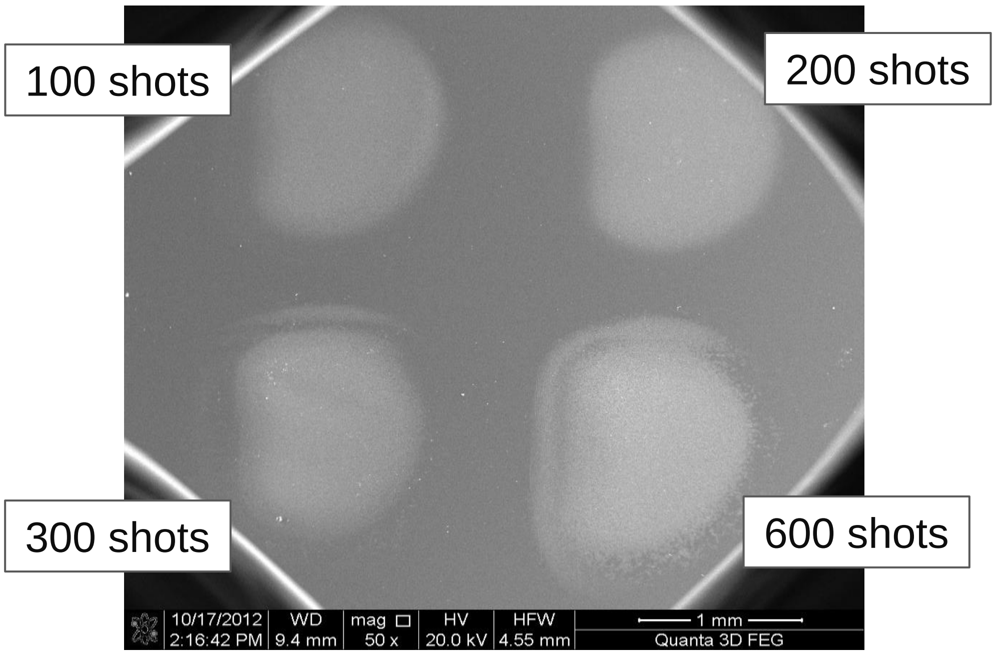
EUV beams

EKSPLA
Rigaku
PREVAC

A.Bartnik et al., *Nucl. Instr. Meth. A* ***647*** *(2011) 125*

EUV modification of polymers

SEM image of EUV irradiated polycarbonate sample with different number of shots



AFM images of EUV irradiated polycarbonate sample

Pristine sample

Sample irradiated with 300 EUV pulses

Doctoral Programme

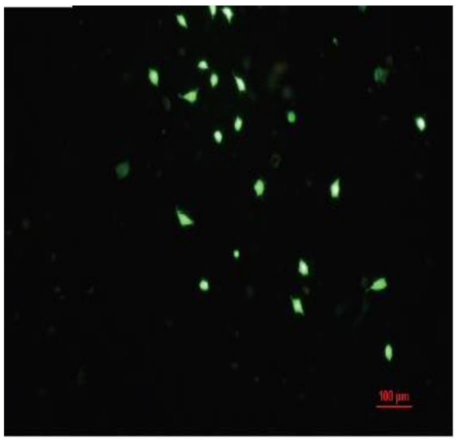
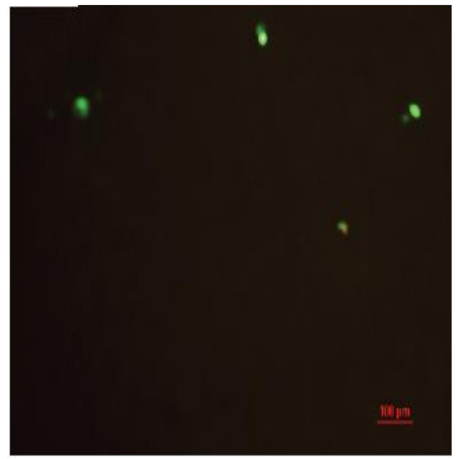
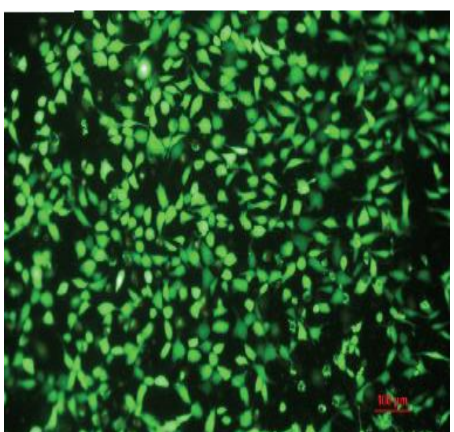
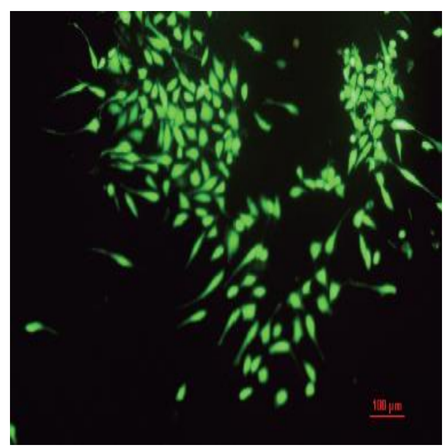
Inam Ul Ahad - Pakistan

I. Ul. Ahad *et al*. J. Biomed. Mater. Res. Part A (2013)

I .U. Ahad *et al*., Acta Phys. Pol. A (2014)

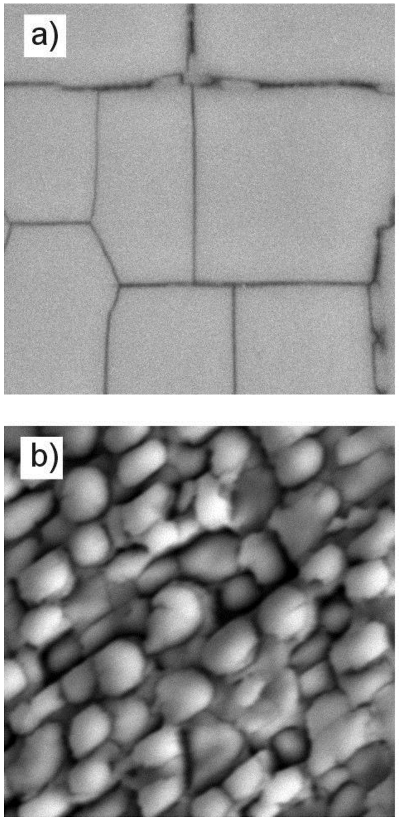
L929 fibroblast surface adhesion

Collaboration with Biomedical Engineering Laboratory WUT (Prof. Tomasz Ciach)

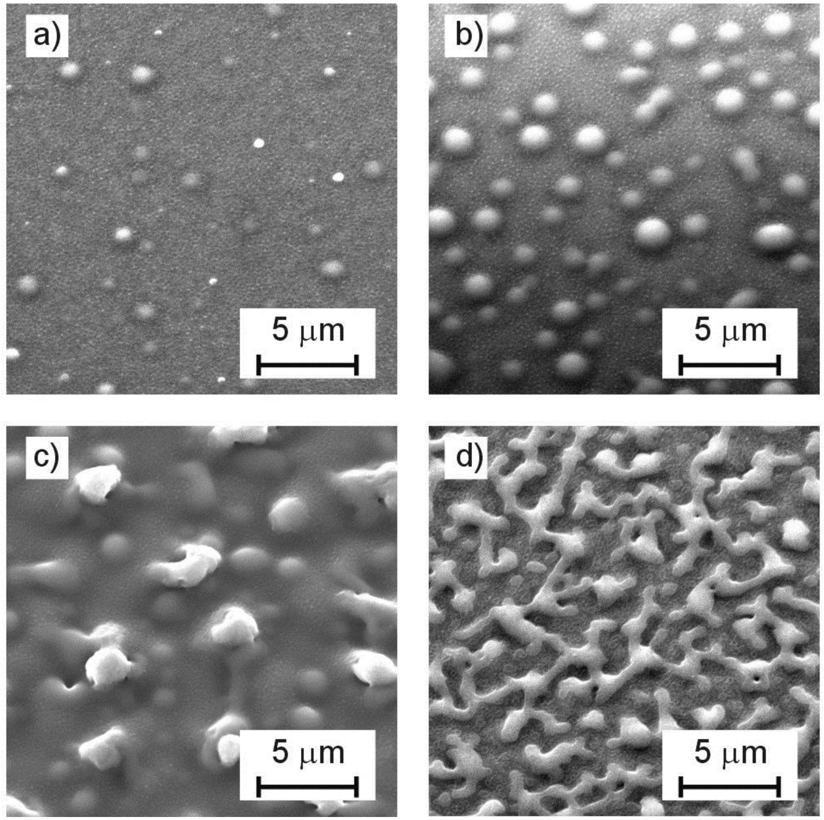
PVF sample	PFTE sample	
		Pristine samples
		Samples irradiated with 300 EUV pulses

I.U. Ahad et al. *NIMB* (2015) – accepted
I.U. Ahad *PhD Thesis* - submitted

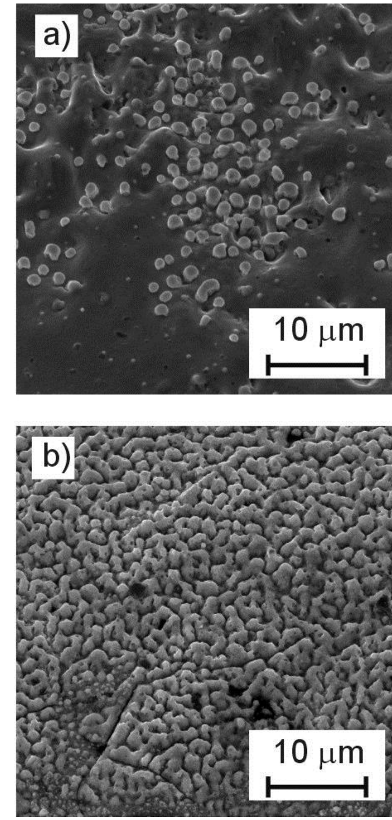
EUV processing of nonorganic materials



Surface cracking,
1min exposure:
a) NaCl,
b) CaF_2



Surface melting, GaAs:
a) 25 pulses, in the focal plane,
b) 50 pulses, in the focal plane,
c) 100 pulses, in the focal plane,
d) 100 pulses, 1 mm downstream the focal plane

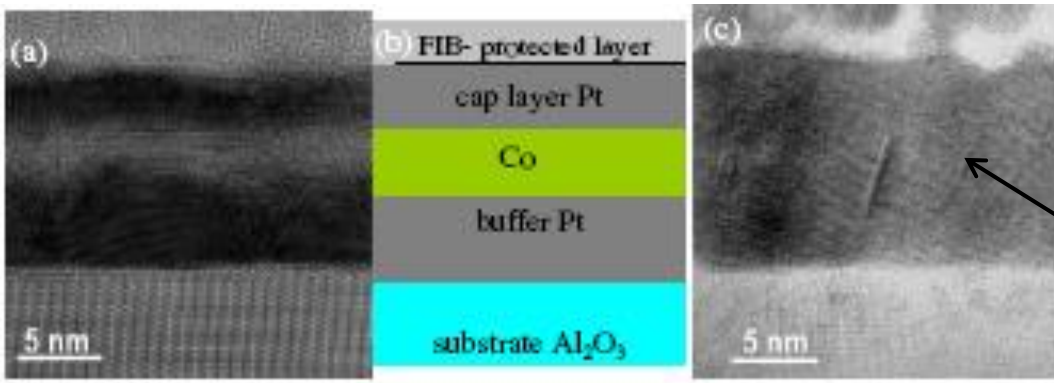


Surface melting, Pb:
a) high fluence,
b) low fluence,
25 pulses

Modification of magnetic materials

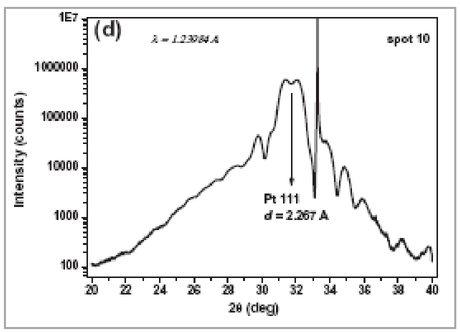
EUV irradiation of ultrathin Pt/Co/Pt trilayer films

External users from University in Białystok and Institute of Physics in Warsaw

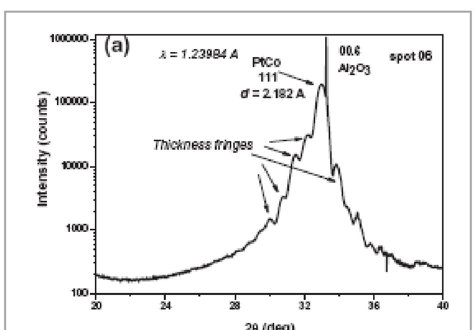


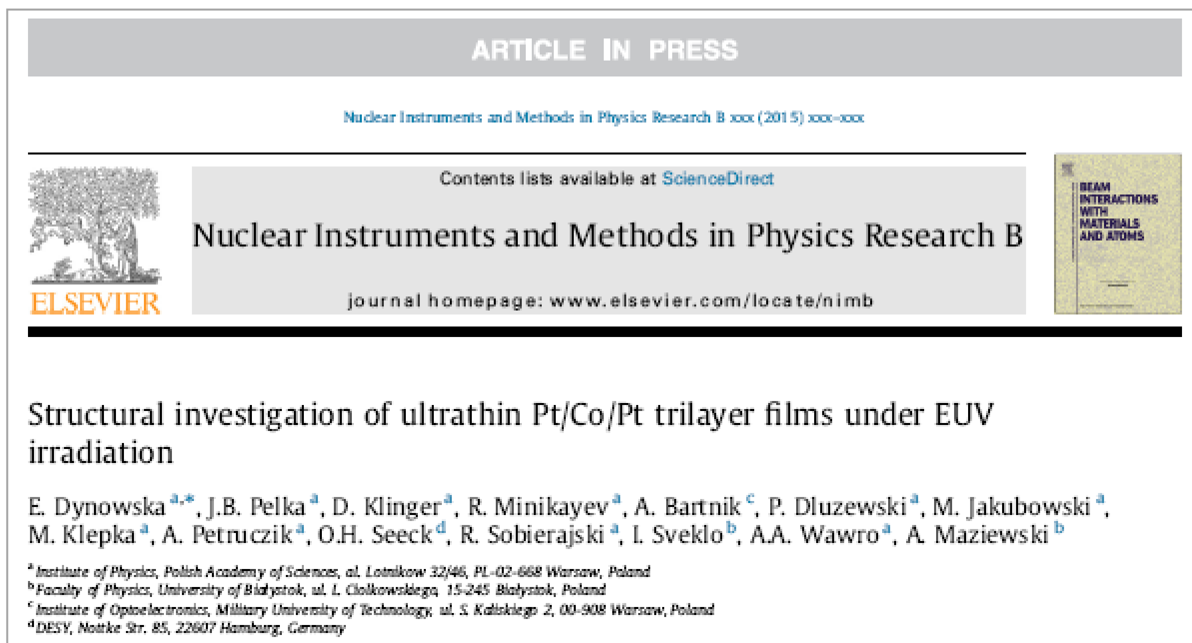
PtCo alloy

XRD



1000 EUV pulses




ARTICLE IN PRESS

Nuclear Instruments and Methods in Physics Research B xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

ELSEVIER

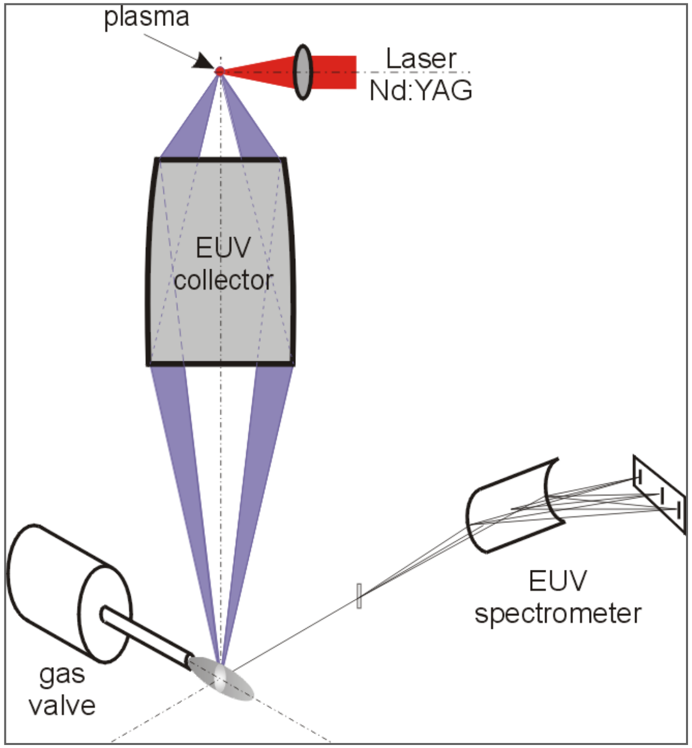
Structural investigation of ultrathin Pt/Co/Pt trilayer films under EUV irradiation

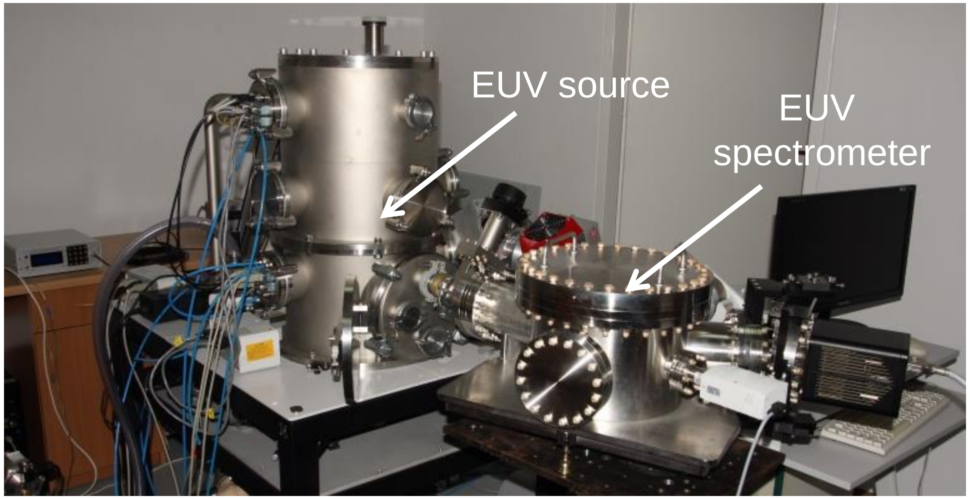
E. Dynowska [a,*], J.B. Pelka [a], D. Klinger [a], R. Minikayev [a], A. Bartnik [c], P. Dluzewski [a], M. Jakubowski [a], M. Klepka [a], A. Petruczik [a], O.H. Seeck [d], R. Sobierajski [a], I. Sveklo [b], A.A. Wawro [a], A. Maziewski [b]

[a] Institute of Physics, Polish Academy of Sciences, al. Lotnikow 32/46, PL-02-668 Warsaw, Poland
[b] Faculty of Physics, University of Bialystok, ul. L. Ciolkowskiego, 15-245 Bialystok, Poland
[c] Institute of Optoelectronics, Military University of Technology, ul. S. Kaliskiego 2, 00-908 Warsaw, Poland
[d] DESY, Notkestr. 85, 22607 Hamburg, Germany

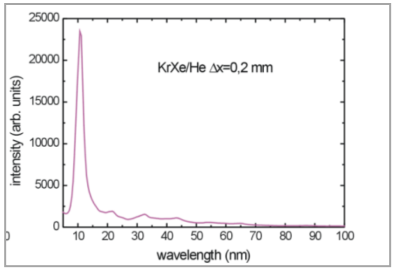
Photoionization of gases with EUV photons

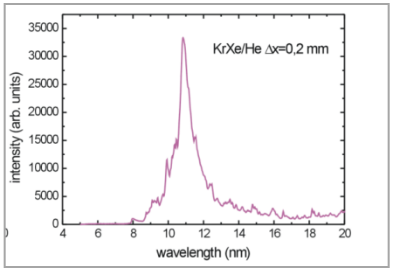
Laboratory astrophysics and astrochemistry

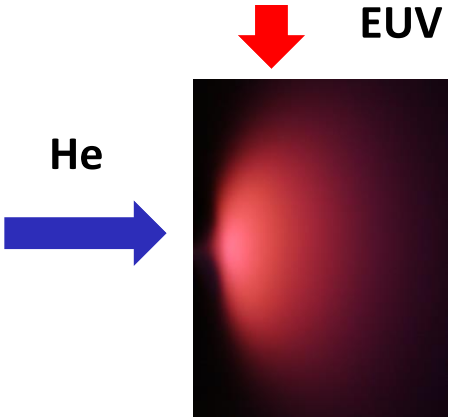


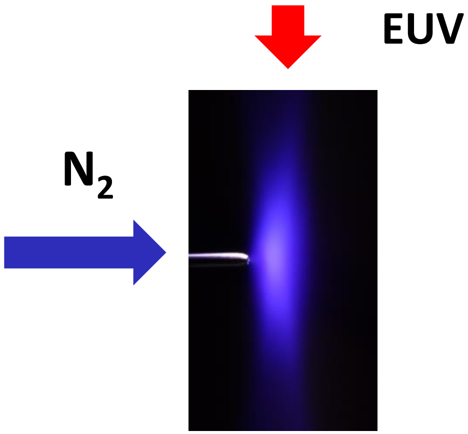


EUV spectra for Kr/Xe



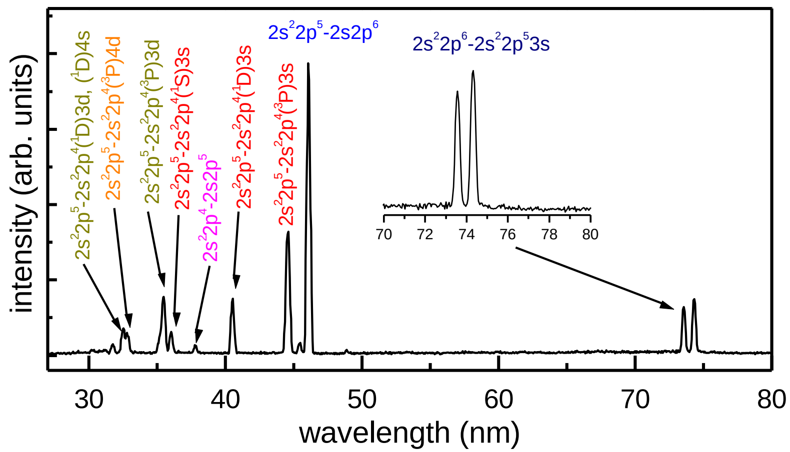






Spectra of EUV photoionized neon

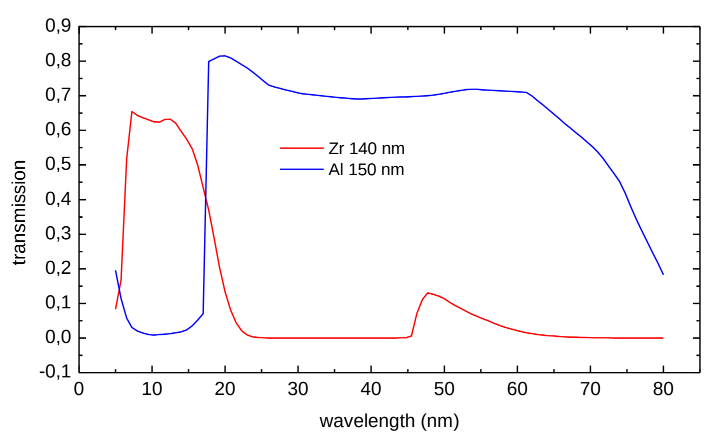
Irradiation in full wavelength range



The excited state $2s2p^6$ appears as a result of photoionization of Ne I from the ground state, hence, high intensity of the $2s^22p^6$ - $2s2p^6$ line.

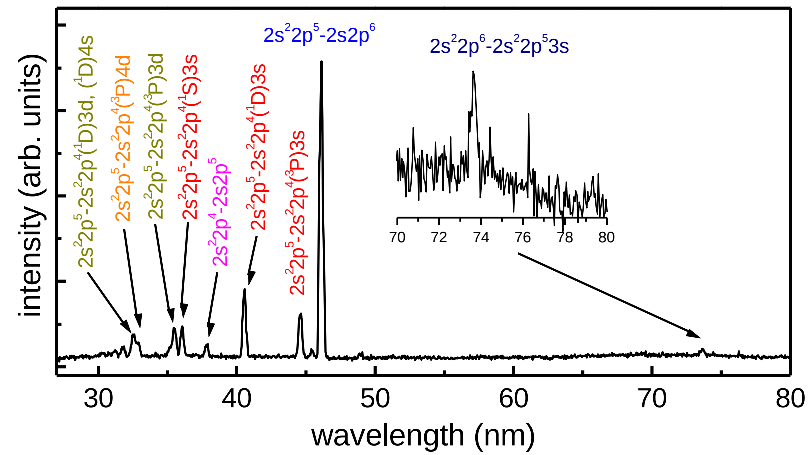
Behaviour of $2s^22p^5$ - $2s^22p^43s$ lines ?

Transmissions of Zr and Al filters



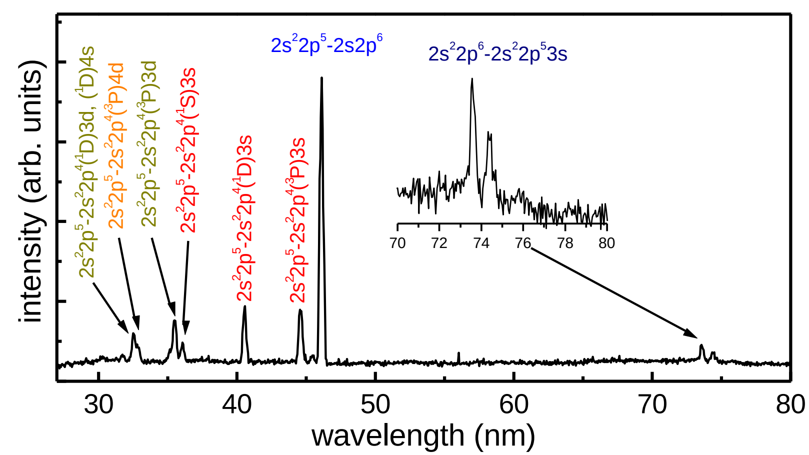
Irradiation through Zr 140 nm

Photoexcitation not possible



Irradiation through Al 150 nm

Photoexcitation possible

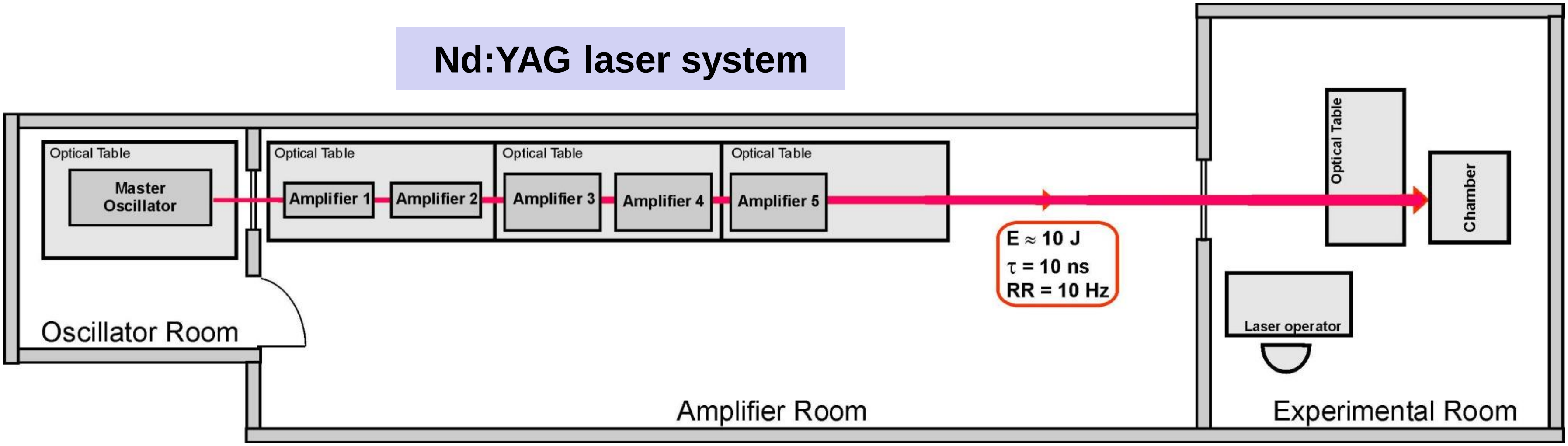


A. Bartnik et al., Rad. Phys. & Chem. **93** (2013) 9

Soft X-ray/EUV source with a 10J Nd:YAG laser

- generation of high-intensity soft X-ray and EUV radiation **(laboratory soft X-ray/EUV beam-line)**
- interaction with gases (photoionization, plasma waveguides)

Nd:YAG laser system

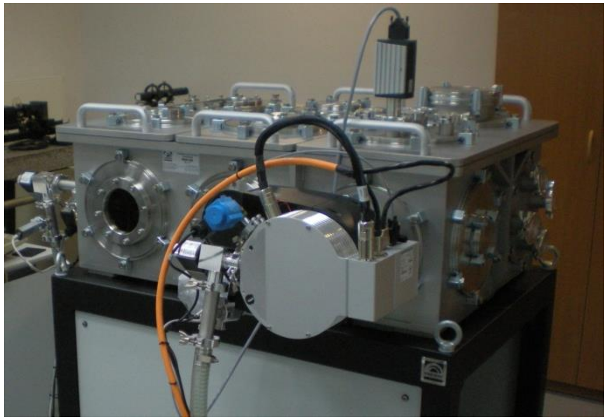


Nd:YAG laser system parameters

- pulse energy 10J
- pulse duration 2-10ns
- repetition rate 10Hz

Laser area

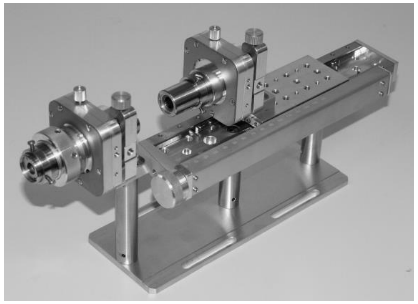
Target area

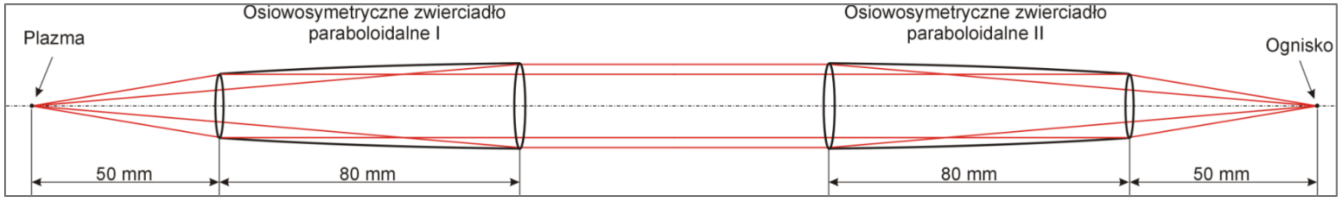


Focusing optics for soft X-ray/EUV radiation

Soft X-ray

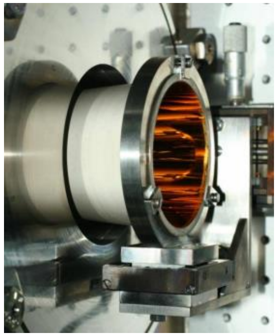
Tandem of axisymmetrical paraboloidal grazing incidence mirrors

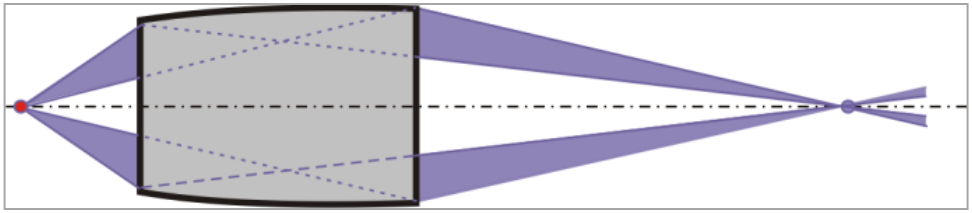




Axisymmetrical ellipsoidal grazing incidence mirror

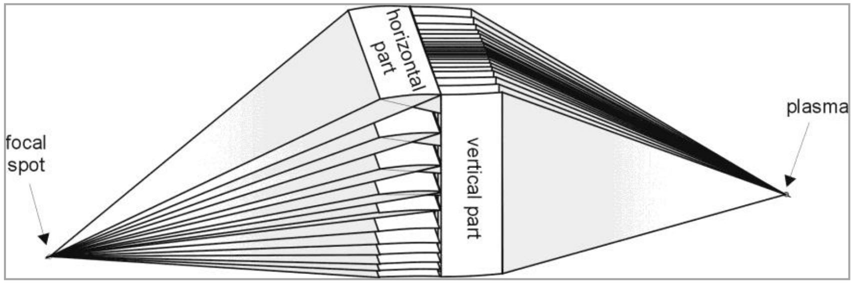
EUV





> 1 J/cm²

Multi-foil grazing incidence mirror



> 0.3J/cm²

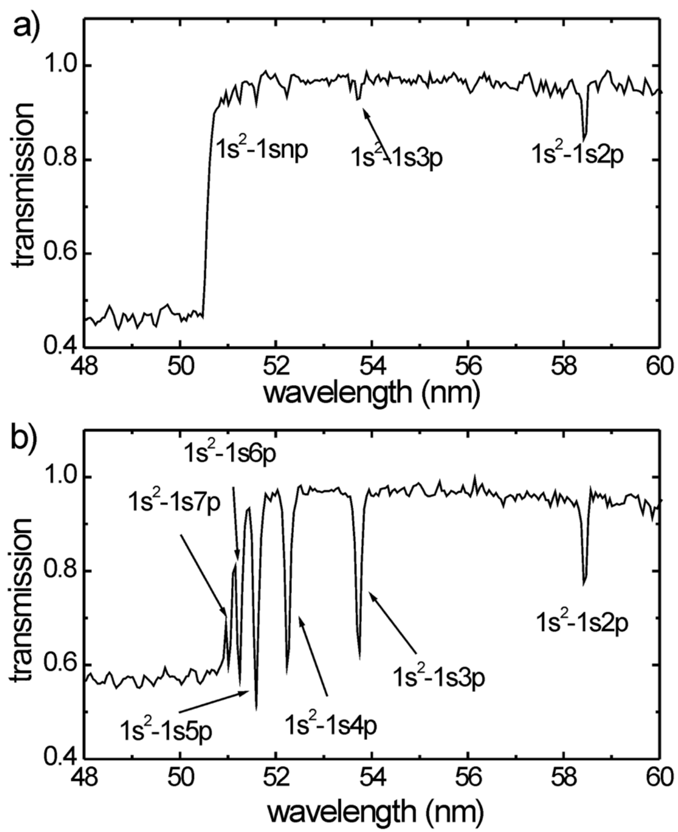
Reflex s.r.o

Rigaku

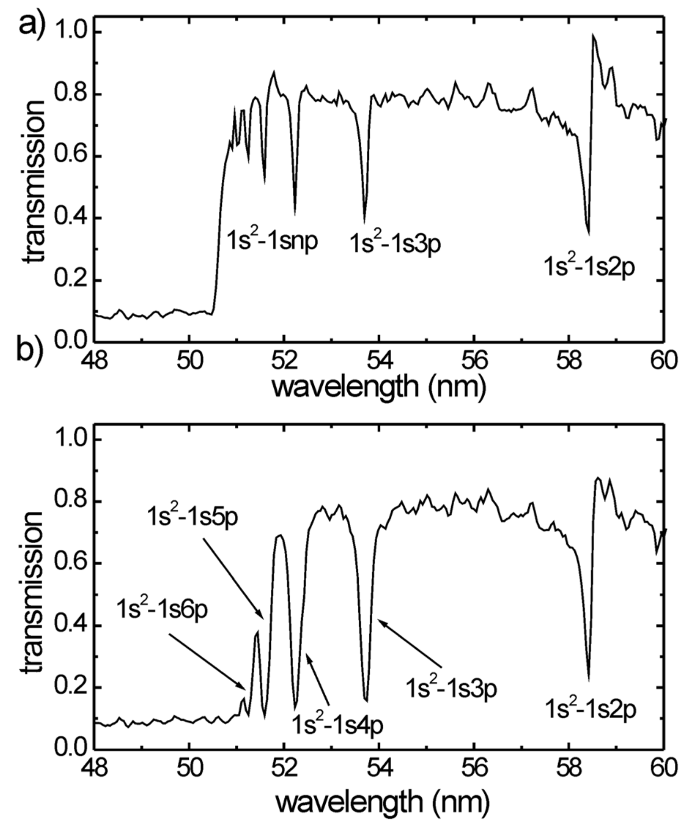
L. Sveda et al., Phys. Scr. 123 (2006) 131, A. Bartnik et al., Phys. Scr. T161 (2014) 014061

EUV absorption spectra of He and photoionized He plasma

Transmission spectra for He
gas density 2×10^{17} cm^3
(a) neutral gas and (b) photoionized plasma.



Transmission spectra for He
gas density 5×10^{18} cm^3
(a) neutral gas and (b) photoionized plasma.

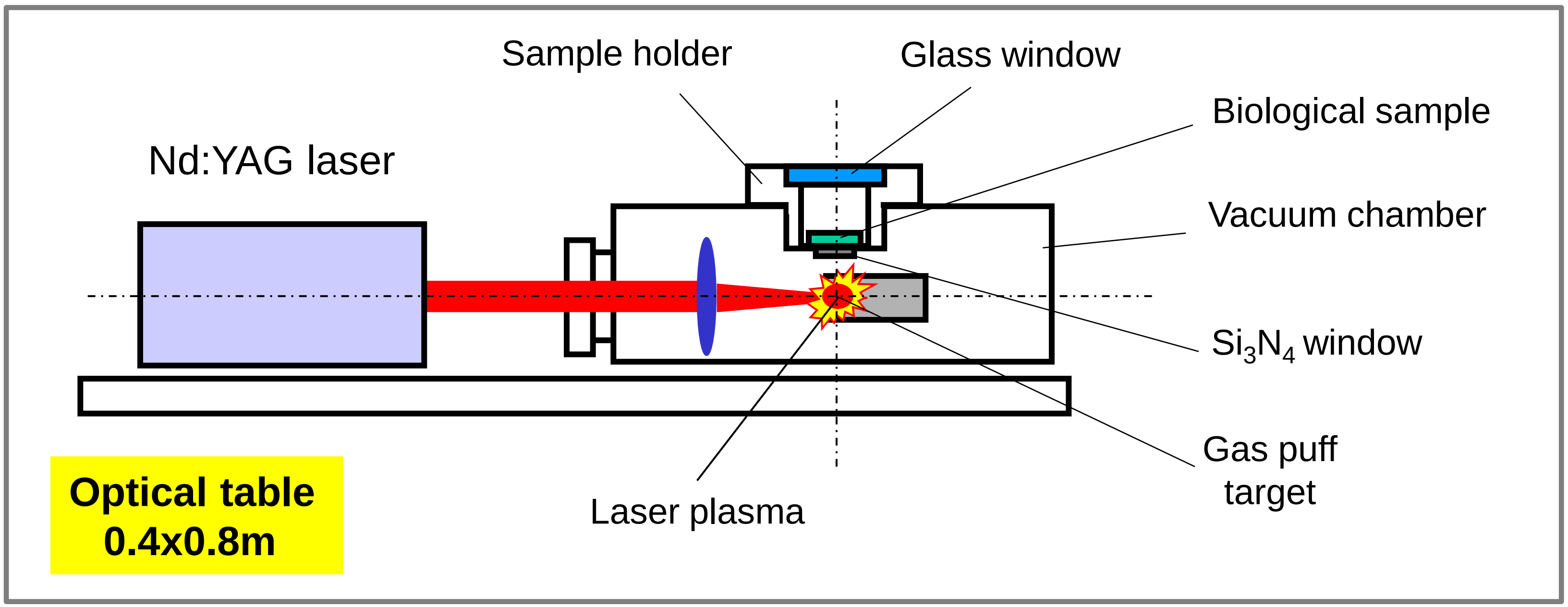


A. Bartnik et al., Phys. of Plasmas **20** (2013) 113302

Laser-plasma soft X-ray source for radiobiology

M. Davıdkova, L. Juha, M. Bittner, S. Koptyaev, J. Krasa, M.Pfeifer, V.Stısova, A. Bartnik, H. Fiedorowicz, J. Mikolajczyk, L. Ryc, L. Pına, M. Horvath, D. Babankova, J. Cihelka, S. Civis
„High-power laser-driven source of sub-nanosecond soft X-Ray pulses for single-shot radiobiology experiments”
Radiat. Res. 168, 382–387 (2007)

Schematic of the laser plasma soft X-ray source for radiobiology



Collaboration with Institute of Nuclear Physics in Cracow

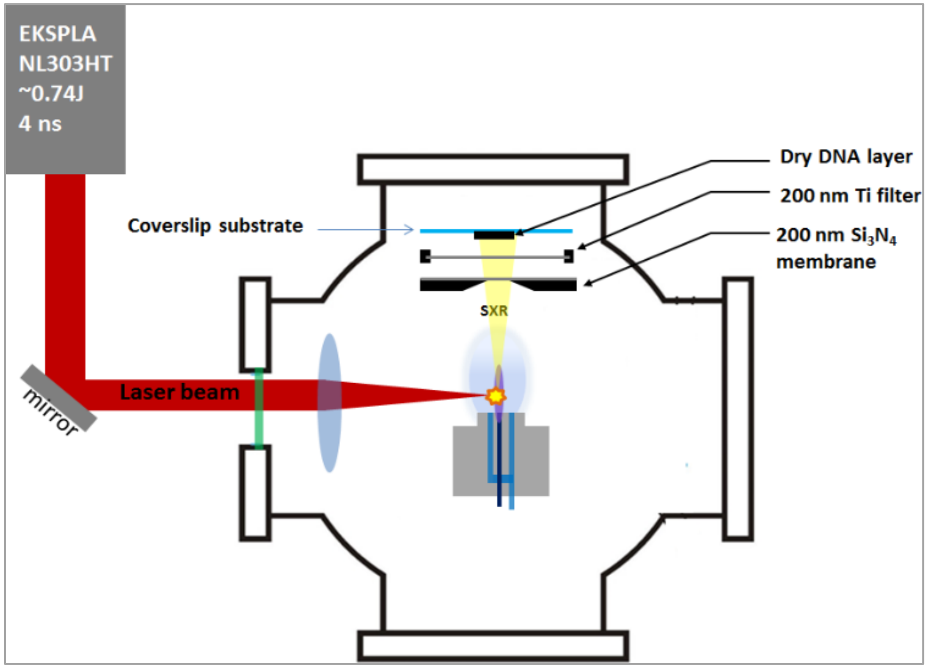
EXTATIC

Doctoral Programme

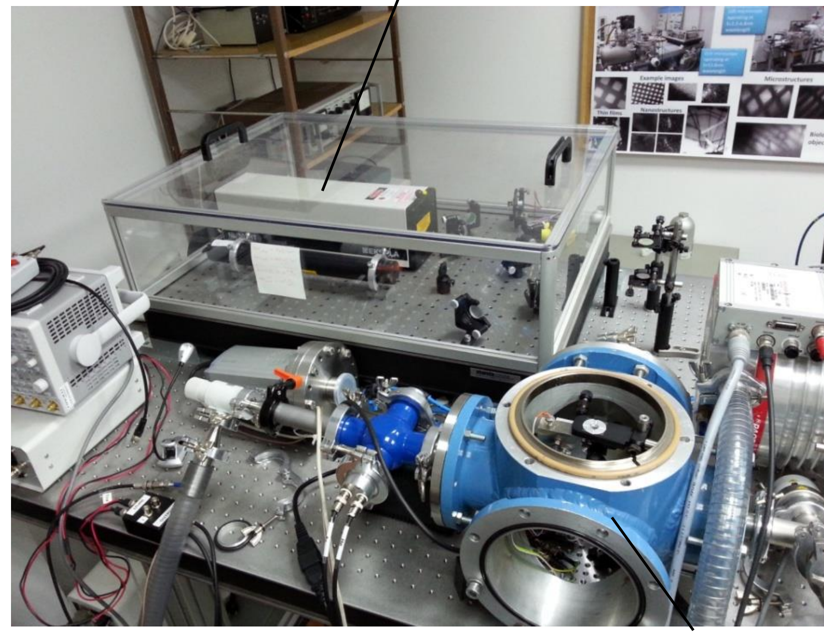
Daniel Adjei - Ghana

Laser-plasma soft X-ray source for radiobiology

Schematic of the source

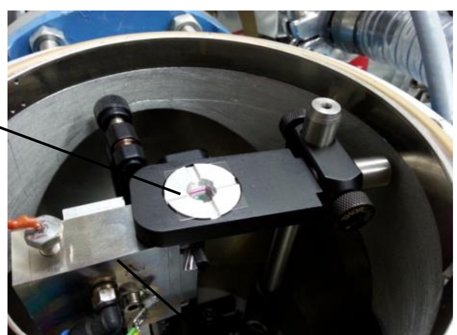


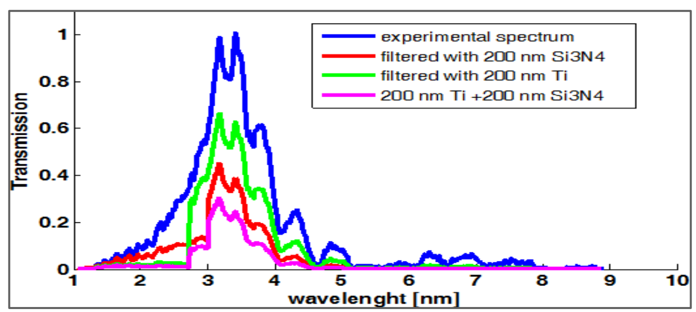
Nd:YAG laser



Source chamber

Sample holder





~ 300 Grey/shot

Gas puff valve

D. Adjei et al. Nucl. Instr. Meth. B (2015) - accepted

Laser-plasma soft X-ray source for radiobiology

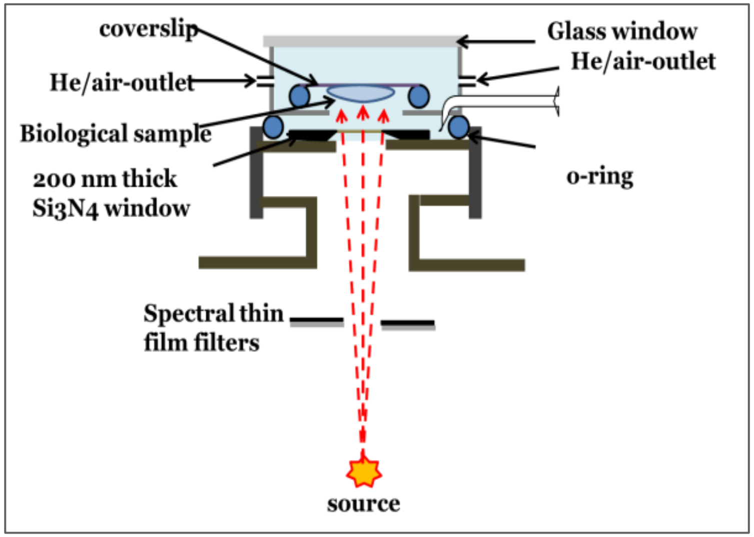
DNA damages induced by soft X-ray pulses from a compact laser plasma source

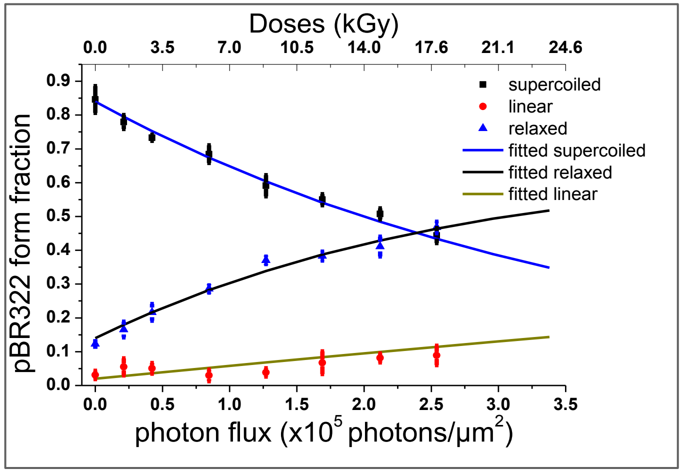
The source has been used to irradiate pBR322 plasmid DNA both in vacuum and the He-environment conditions.

Single and double strand breaks were quantified by gel electrophoresis.

The number of strand breaks increased with increasing dose of the “water window” soft X-rays.

The strand breaks of plasmid solution irradiated in helium condition may be associated with damage from water free radicals.

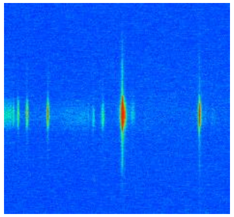




D. Adjei et al. Rad. Phys. Chem. (2015) - submitted

Collaboration with the Institute of Nuclear Physics, Cracow

Summary



- laser plasma EUV and soft X-ray sources based on a **gas puff target** have been developed,
- applications in **metrology, microscopy, radiography** and **tomography, processing of materials** and **photoionization studies** were demonstrated,
- research on applications in **contact microscopy** and **radiobiology** are under way.

ACKNOWLEDGEMENTS

The research was supported by the Ministry of Science and Higher Education of Poland (EUREKA project E! 3892 ModPolEUV and COST Action MP0601 project), the Foundation for Polish Science (HOMING 2009 Programme), the National Centre for Research and Development (LIDER Programme) and the European Comission (ELI, Laserlab Europe, EXTATIC, CEZAMAT and OPTOLAB projects).

Erasmus Mundus Joint Doctorate Programme

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RWTH AACHEN UNIVERSITY, Germany
UNIVERSITY COLLEGE DUBLIN, Ireland
UNIVERSITY OF PADUA, Italy
UNIVERSITY OF SOUTHAMPTON, United Kingdom

1. Modification of polymer surfaces with EUV photons for application in biomedical engineering (**Inam Ul Ahad** - Pakistan) - PhD awarded
2. Application of laser plasma soft X-ray sources in radiobiology studies (**Daniel Adjei** – Ghana)
3. Soft X-ray contact microscopy using a compact laser plasma light source (**Mesfin Getachew Ayele** – Etiopia)
4. Nanoscale imaging using compact laser plasma SXR sources based on a double stream gas-puff target and Fresnel optics (**Alfio Torrisi** – Italy)
5. Photoionization of gases and clusters by intense pulses of extreme ultraviolet (**Ismail Saber** – Sudan)

Laserlab Europe

Laserlab
Europe

European project under 7th FP

LASERLAB-EUROPE

The Integrated Initiative of European Laser Laboratories

National resources:

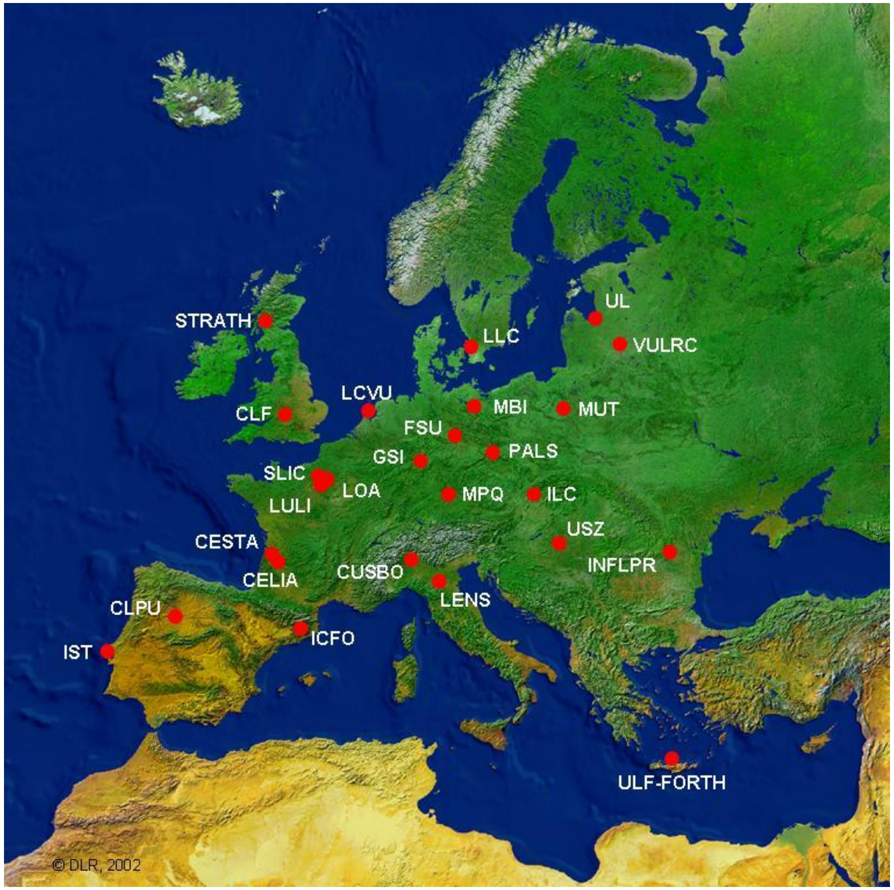
27 laser infrastructures from 16 countries

Activities:

- Networking
- JRAs
- Access

Continues under Horizon2020

High intensity lasers in LASERLAB-EUROPE



www.laserlab-europe.eu

Training in laser plasma sources of soft X-rays and EUV

Short-term training visits

We offer:
- scientific program
- accommodation
- meals

Scientific program:
- introduction
- sources
- SEM
- AFM
- XPS

INSTITUTE OF OPTOELECTRONICS
Military University of Technology

LASERLAB EUROPE User Training in Lasers and Applications

Training on Laser Plasma X-ray and EUV Sources for Application in Nanotechnology and Biomedical Engineering

The Training Visits on Laser Plasma X-ray and EUV Sources for Application in Nanotechnology and Bioengineering are organized at the Institute of Optoelectronics MUT under the Laserlab Europe project. The training is intended to teach and to increase the experience of the potential User on the laser plasma sources of X-rays extreme ultraviolet (EUV) and their applications.

The aim of the Training Visits is to improve the experimental skills and competencies of students and doctoral candidates in the area related to generation of X-ray and EUV radiation with lasers and its application in nanotechnology and biomedical engineering. The main goal is to increase the User's interest to the laser plasma EUV sources based on a gas puff target, start the domestic and international collaboration and develop a community of Users.

The Training Visit covers lectures introducing to the topics provided by specialists in the field and laboratory trainings performed at the Laser-Matter-Interaction (LMI) laboratory.

Detailed information on the Training Visits and the application procedure are given at the LMI website: (www.ztl.wat.edu.pl/zoplzm).

Institute of Optoelectronics, Military University of Technology, 2 Kaliskiego St., 00-908 Warsaw, Poland
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EXTATIC

Training Visits in Laser Plasma X- ray and EUV Sources for Application in Nanotechnology and Biomedical Engineering

Call for applications for Training Visits

Local Organizer: Institute of Optoelectronics, Military University of Technology (IOE-MUT)
Research Group: Laser-Matter Interaction (LMI) Group
Number of participants: 2 - 4
Training duration: any time

Detailed programme and aim of the Training Visits:

These short-term **Training Visits** are intended to teach or to increase experience of a potential User on laser plasma X-ray and extreme ultraviolet (EUV) sources. The aim of the visits is to improve the experimental skills and competencies of students and doctoral candidates in the area related to generation of X-ray and EUV with and its application in nanotechnology and biomedical engineering. The **Training Visits** will be carried out at the Laser-Matter Interaction (LMI) Laboratory that poses an unique equipment and know-how on generation of X-rays and extreme ultraviolet using laser plasma sources based on a gas puff target approach. During the training visits it is planned to provide lectures to introduce the participants into the subject and give background knowledge needed for the practical training in the laboratory. The laboratory training will be oriented on the use of the laser plasma X-ray and EUV sources in experimental studies on interaction of energetic photons with matter, processing materials and modification of polymer surfaces for biocompatibility control and application in nanoimaging and pulsed microradiography and tomography.

During the training visits we offer the scientific and technical assistance, access to the research infrastructure, accommodation and meals at the university guest house. The support for the **Training Visits** will be granted on the basis of applications which will be evaluated by experts.

How to apply: Please complete the application form (form) and send it to the Training Supervisor and the Contact Persons.

Remarks:

We would like to encourage to participate in the **Training Visits**, since we already have the experience in organizing similar schools and short-term scientific visits performed under the Laserlab Europe project, in the frame of bilateral co-operation and under the COST Action MP0601 Short Wavelength Laboratory Sources (Training School on "EUV Optics and Technology" and Short Term Scientific Missions).

For further details on the experimental capabilities and research opportunities please visit Laser Matter Interaction Group website: http://www.ztl.wat.edu.pl/zoplzm. For more information regarding the Training School and technical assistance in completing the application, please contact:

Training Supervisor:

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http://www.ztl.wat.edu.pl/zoplzm

LASERLAB-EUROPE Technical Workshops

1st Workshop on Application of Laser Plasma Sources of Soft X-rays and EUV

Laser-Matter Interaction Group Web Page

http://www.ztl.wat.edu.pl/zoplzm

EUV beam